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# Relative sea-level change in western New Guinea recorded by regional biostratigraphic data

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## Abstract

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## Disciplines

Medicine and Health Sciences | Social and Behavioral Sciences

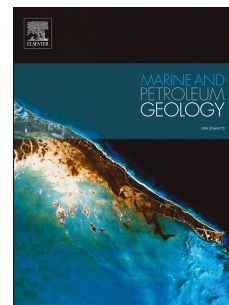
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**Relative sea-level change in western New Guinea recorded by regional  
biostratigraphic data**

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**Abstract**

We present new biostratigraphic analyses of approximately 200 outcrop samples and review biostratigraphic data from 136 public domain exploration wells across western New Guinea. Biostratigraphic ages and palaeodepositional environments were interpreted from occurrences of planktonic and larger benthic foraminifera, together with other fossils and environmental indicators where possible. These data were compared with existing geological maps and exploration well data to reconstruct the palaeogeography of western New Guinea from the Carboniferous to present day. In addition, we used the known bathyal preferences of fossils to generate a regional sea-level curve and compared this with global records of sea-level change over the same period. Our analyses of the biostratigraphic data identified two major transgressive-regressive cycles in regional relative sea-level, with the highest sea levels recorded during the Late Cretaceous and Late Miocene and terrestrial deposition prevalent across much of western New Guinea during the Late Paleozoic and Early Mesozoic. An increase in the abundance of carinate planktonic foraminifera indicates a subsequent phase of relative sea-level rise during a regional transgressive event between the Late Jurassic and Late Cretaceous. However, sea-levels dropped once more during a regressive event between the Late Cretaceous and the Paleogene. This resulted in widespread shallow water carbonate platform development in the Middle to Late Eocene. A minor transgressive event occurred during the Oligocene, but this ceased in the Early Miocene, likely due to the collision of the Australian continent with intra-Pacific island arcs. This Miocene collision event resulted in widespread uplift that is marked by a regional unconformity. Carbonate deposition continued in platforms that developed in shallow marine settings until these were drowned during another transgressive event in the

Middle Miocene. This transgression reached its peak in the Late Miocene and was followed by a further regression culminating in the present day topographic expression of western New Guinea.

**Keywords:** Tectonics; foraminifera; palaeogeography; biogeography; eustasy;

## 1. Introduction

New Guinea has represented the northernmost boundary of the Australian Plate from the present until at least the Permian (perhaps as early as the Carboniferous). During this time New Guinea was part of an Andean-style continental arc system that extended around a large portion of Gondwana (Charlton, 2001; Hall 2002; 2012; Hill and Hall 2003; Crowhurst et al., 2004; Metcalfe 1998; 2009; Gunawan et al., 2012; 2014; Webb and White, 2016). This long-lived plate boundary records evidence of numerous tectono-thermal events during the Paleozoic, Mesozoic and Cenozoic (e.g. Visser and Hermes, 1962; Pieters et al., 1983; Davies and Jaques 1984; Pigram and Davies 1987; Pigram and Symonds 1991; Baldwin and Ireland 1995; Baldwin et al., 2004; 2012; Davies, 2012; Bailly et al., 2009; Holm and Richards, 2013; Holm et al., 2015; 2016; François et al., 2016). However, much of the geology of New Guinea is also dominated by siliciclastic and carbonate deposition during seemingly long periods of quiescence (Pieters et al., 1983; Pigram; Visser and Hermes, 1962; Fraser et al., 1993; Hill, 1991; Davies, 2012; Baldwin et al., 2012). We focus on the age and depositional environment of these sediments in western New Guinea, an area that is relatively underexplored, with the last major geological mapping campaign being conducted in the 1980's (e.g. Masria et al., 1981; Pieters et al., 1983; Dow et al., 1986; Atmawinata et al., 1989; Pieters et al., 1989; Dow et al.,

1990; Harahap et al., 1990; Pieters et al., 1990; Robinson et al., 1990; Panggabean et al., 1995). We present new biostratigraphic age data based on benthic and planktonic foraminifera, as well as facies analyses from nearly 200 outcrop samples from western New Guinea. Where possible, we compared these results with publicly available hydrocarbon exploration well locations, biostratigraphic analyses and interpreted depositional environments (e.g. Visser and Hermes, 1962; Fraser et al., 1993). The aim of this work was to better establish the duration and facies distribution of strata to better understand the spatio-temporal distribution of periods of quiescence at the northern margin of the Australian Plate between the Silurian and present day. We begin by reviewing the existing literature on the geology of western New Guinea. We then discuss the newly obtained biostratigraphic data as well as data obtained from a meta-study of publically available biostratigraphic data from exploration wells, and what these mean for our understanding of changing palaeoenvironments.

### 1.1 Geological mapping of western New Guinea

The first comprehensive geological mapping of Indonesian New Guinea was conducted between 1935 and 1960 by geologists of the Nederlandsche Nieuw Guinee Petroleum Maatschappij. The results of this work are compiled and summarised in Visser and Hermes (1962). The observations reported in this work lay the foundation for the stratigraphy of western New Guinea and remain highly relevant, despite this work being completed before the advent of plate tectonics. The stratigraphy and tectonic development of western New Guinea was refined by Indonesian and Australian government geologists between 1978 and 1982; the results of which are summarised in Pieters et al. (1983). Subsequent work has

predominantly been driven by hydrocarbon or mineral exploration in the region (e.g. White et al., 2014) and broadly consists of reviews of the stratigraphy (e.g. Fraser et al., 1993), the regional tectonic evolution (e.g. Decker et al., 2009; Baldwin et al., 2012; Davies 2012) or targeted geological studies that have broadly focused on the evolution and uplift of basement rocks (e.g. Bailly et al., 2009; François et al., 2016; Webb and White 2016).

## 1.2 The Bird's Head, Neck, Body and Tail

New Guinea is often described to reflect the shape of a bird, comprising the Bird's Head, Neck, Body, and Tail from west to east, respectively (Fig. 1). The Bird's Head and Neck, and part of the Body are within the Indonesian provinces of West Papua and Papua (formerly known as Irian Jaya). The rest of the Bird's Body and the Tail are found in Papua New Guinea. The island's peculiar morphology largely reflects the geology and tectonic evolution of the island. For example, the Bird's Neck is largely composed of limestones and siliciclastic rocks shortened during the development of the Lengguru Fold and Thrust Belt (e.g. Bailly et al., 2009; François et al., 2016)(Fig.1). These deformed rocks form part of a mountain belt that extends from western New Guinea (the Bird's Head), along the Lengguru Fold and Thrust Belt (the Bird's Neck), continuing along the Central Range (the Bird's Body) to the eastern tip of the island (Bird's Tail) (Fig. 1). Rocks to the south of New Guinea are primarily of Australian continental affinity whereas those to the north consist of ophiolite and island arc volcanics of Pacific Plate provenance. The two domains are separated by a central, complex region of juxtaposed fault slices of sediments together with variably metamorphosed and granitic rocks. This juxtaposition marks a suture that formed during arc-continent collision between the Oligocene and Early



127 Miocene, (Fig. 1) (e.g. Pieters et al., 1983; Milsom, 1992). Thus the stratigraphy of  
128 the Bird's Head can be broadly described as intra-Pacific island arc material to the  
129 north and east, which accreted to Australian continental material to the south and  
130 west. The post-collisional stratigraphy of both domains is reasonably contiguous.  
131

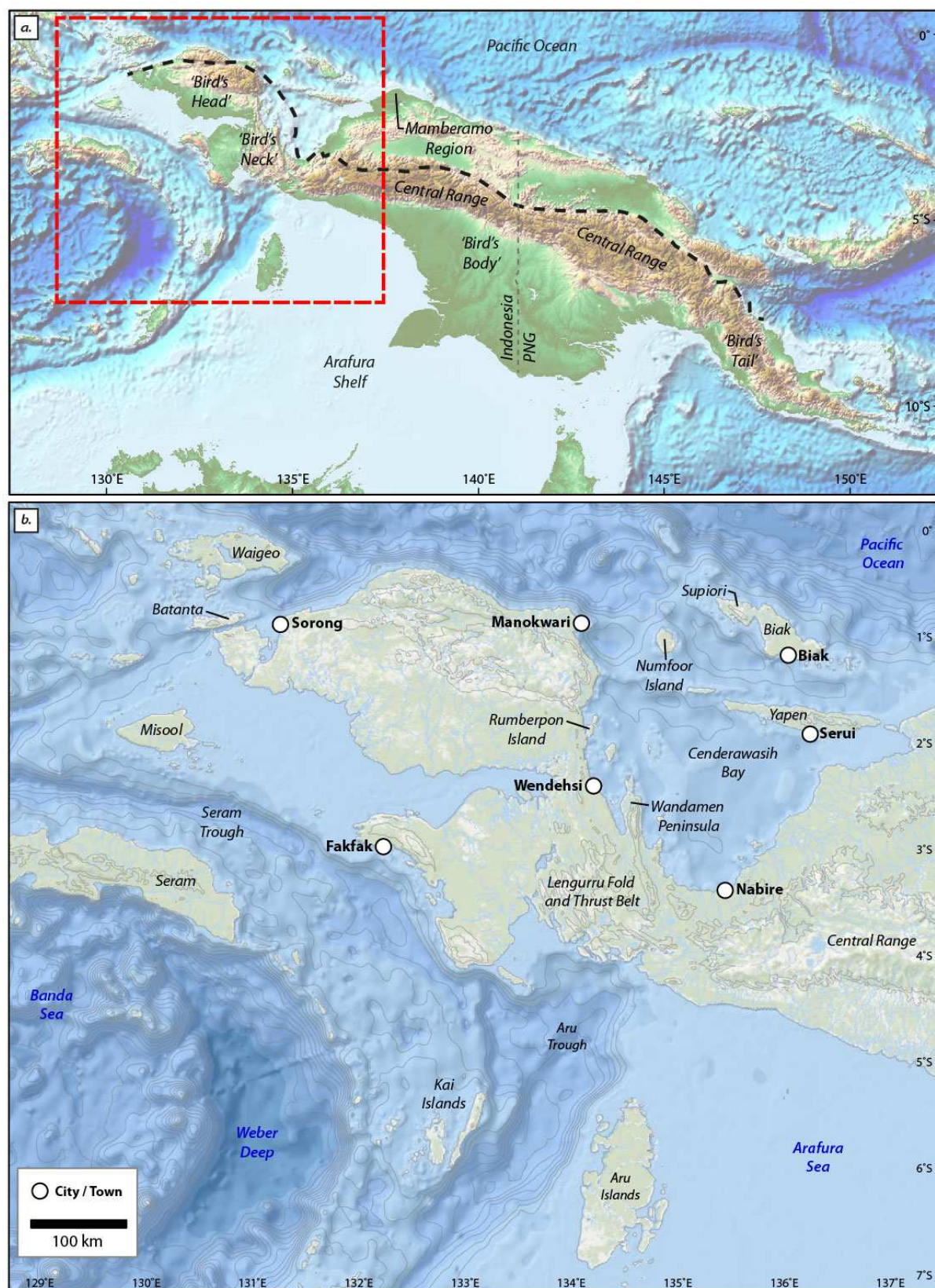


Figure 1.

## 2. Depositional history of western New Guinea sediments

### 2.1 Australian Plate stratigraphy

A simplified map showing the distribution of sedimentary, igneous and metamorphic rocks mapped by Masria et al., (1981); Pieters et al. (1983); Dow et al. (1986); Atmawinata et al. (1989); Pieters et al. (1989); Dow et al. (1990); Harahap et al. (1990); Pieters et al. (1990); Robinson et al. (1990); Panggabean et al. (1995) is shown in Figure 2. The oldest strata within the Bird's Head consist of variably metamorphosed siliciclastic rocks that were most likely derived from rocks to the south (i.e. eroded Australian/Gondwanan crust) (e.g. Decker et al., 2017) (Fig. 2 and 3). The variably metamorphosed rocks in the Bird's Head Peninsula have poor age control, but were assigned a Silurian-Devonian age from several graptolites and because these rocks are cross-cut by Carboniferous and Permian intrusions (Visser and Hermes, 1962; Pieters et al., 1983) (Fig. 2 and 3). These sequences are known as the Kemum and Aisasjur Formations (Fig. 3) and are considered to represent distal and proximal turbidite deposits, respectively (Visser and Hermes, 1962; Pieters et al., 1983). The low metamorphic grade turbidite sequences of the pre-Middle Triassic Ligu Formation in Misool are potentially equivalent to those classified as the Kemum Formation (Hasibuan, 2012). Other Devonian to Late Proterozoic siliciclastic and carbonate sequences are exposed in parts of Papua New Guinea (e.g. Modio Formation, Tuaba Formation, Karieum Formation) along with the Late Proterozoic–Cambrian metamorphosed basaltic rocks of the Awitagoh and Nerewip formations (Davies, 2012 and references therein) (Fig. 3). The oldest carbonate unit in western New Guinea is the Modio Dolomite of the Central Ranges. This was deposited during the Devonian or possibly as early as the Silurian (Fig. 3; Pieters et al., 1983; Nicoll

and Bladon, 1991; Oliver Jr. et al., 1995; Parris, 1994; Cloos et al., 2005; Davies, 2012).

During the Carboniferous, a phase of magmatism was suggested from K-Ar dating of porphyritic dacite and altered porphyritic igneous rocks from the Melaiurna Granite (Bladon, 1988). Despite this volcanism, the Carboniferous to Permian was a period of relatively stable paralic sediment deposition, with occasional shallow marine incursions marked by thin limestone beds in New Guinea's Central Range. The Permo-Carboniferous Aifam Group (Fig. 3) contains various terrestrial and marine deposits (Visser and Hermes 1962, Chevallier and Bordenave, 1986, Dow et al., 1986). This group consists of the Aima, Ainim and Aiduna formations which collectively consist of conglomerates, red beds and coal seams that were likely deposited in a terrestrially influenced, possibly deltaic and/or lacustrine setting (Norvick et al., 2003). The Aifat Mudstone, which also forms part of the Aifam Group however most likely represents deposition in deeper water, perhaps in a basinal setting (Pieters et al., 1983).



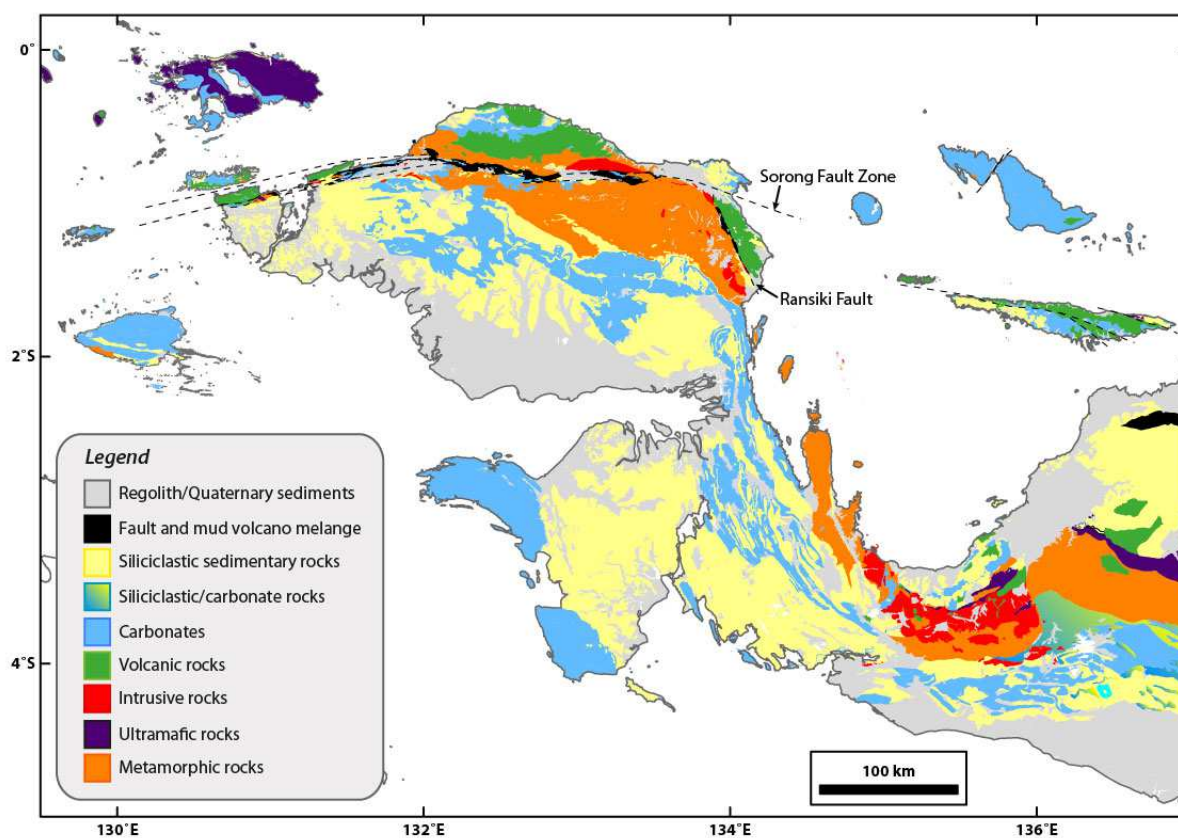


Figure 2.

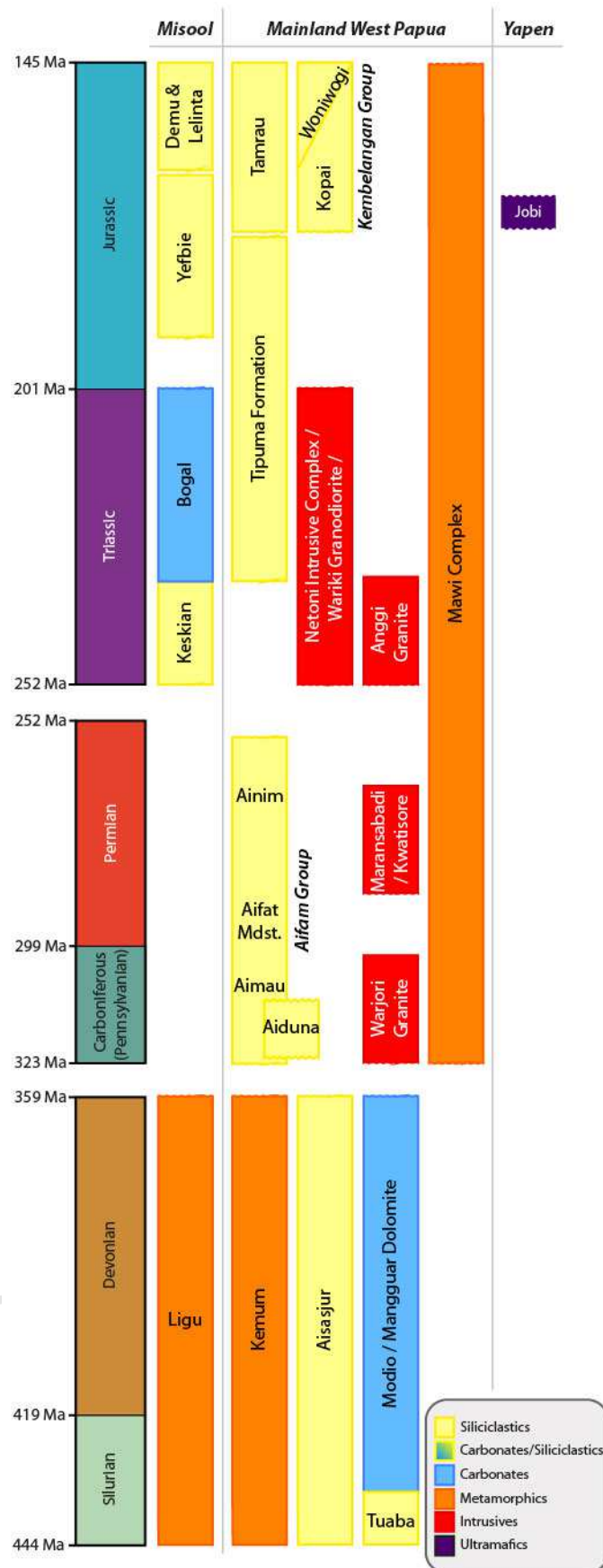


Figure 3.

Volcanic activity recommenced or became much more extensive during the Triassic. The evidence for this is taken from various granitoids found in the Bird's Head Peninsula and on the western and southwestern sections of Cenderawasih Bay (Fig. 2). The granitoids include the Netoni Intrusive Complex, Anggi Granite, Wariki Granodiorite, Warjori Granite and this magmatic belt likely continues further to the east, along the length of New Guinea (e.g. Bladon, 1988; Crowhurst et al., 2004; Webb and White, 2016). Additional supporting evidence for this Triassic magmatism comes from detrital zircon age dates together with volcanic quartz found in ash fall and fluvial sequences of the Tipuma Formation (Gunawan et al., 2012; 2014) (Fig. 3). It was likely that the Triassic magmatism was coeval with carbonate deposition – the closest evidence for this is taken from the Late Triassic Manusela and Asinepe Limestone formations of Misool and Seram respectively (Pieters et al., 1983; Martini et al., 2004). The deposition of these sequences continued into the early to middle Jurassic with deposition occurring in shallow seas with little siliciclastic input. There was a greater and increasing proportion of siliciclastic material being deposited in the Bird's Head Peninsula during the Jurassic and into the Late Cretaceous. This consisted of the deposition of the Tamrau Formation and Kembelangan Group (Fig. 4) which are broadly equivalent to the shelfal deposits of the Demu and Lelintu Formations of Misool (Hasibuan, 1990) (Fig. 4).

The Cretaceous siliciclastic units of the Kembelangan Group include the Jass Formation, Piniya Mudstone and the Woniwogi and Ekmai Sandstones (Fig. 4). Carbonate deposits in the Bird's Head are not known until the Late Cretaceous (Pieters et al., 1983). These include Coniacian to Maastrichtian age siliciclastics of

the Ekmai Sandstone which pass laterally into the deep-water pelagic carbonates of the Simora Formation (Fig. 4; Brash et al., 1991). Fragments of inoceramid bivalves within the base of the conformably overlying Waripi Formation suggest a Late Cretaceous age for the base of this unit.

From the Late Cretaceous to early Paleogene there is a distinct change from siliciclastic to carbonate deposition recorded across the Bird's Head (Fig. 4). Visser and Hermes (1962) proposed the name 'New Guinea Limestone Group' (NGLG) to include Late Cretaceous to Middle Miocene limestones. The NGLG is between 1km and 1.6km thick, and crops out in the western Bird's Head, the Lengguru Fold and Thrust Belt, the Central Range and in parts of Papua New Guinea (Brash et al., 1991; Fig. 3). The Waripi Formation represents the oldest Paleogene strata of the NGLG. These were deposited in shallow-water areas of a new Cenozoic basin from the middle to late Paleocene (Brash et al., 1991; Fig. 4). However, turbidite deposits of the Daram Formation were deposited in deep-water areas to the north of this basin (Norvick et al., 2003). The Imskin Limestone (part of the NGLG) may interfinger with the Waripi Formation in these deep-water areas (Brash et al., 1991) (Fig. 4). The Cenozoic basin was relatively stable throughout the Eocene, depositing the shallow-water Faumai and Lengguru Limestones, while the Imskin Limestone continued accumulating pelagic carbonate up until collision with an intra-Pacific island arc between the Oligocene and Early Miocene (Fig. 4).



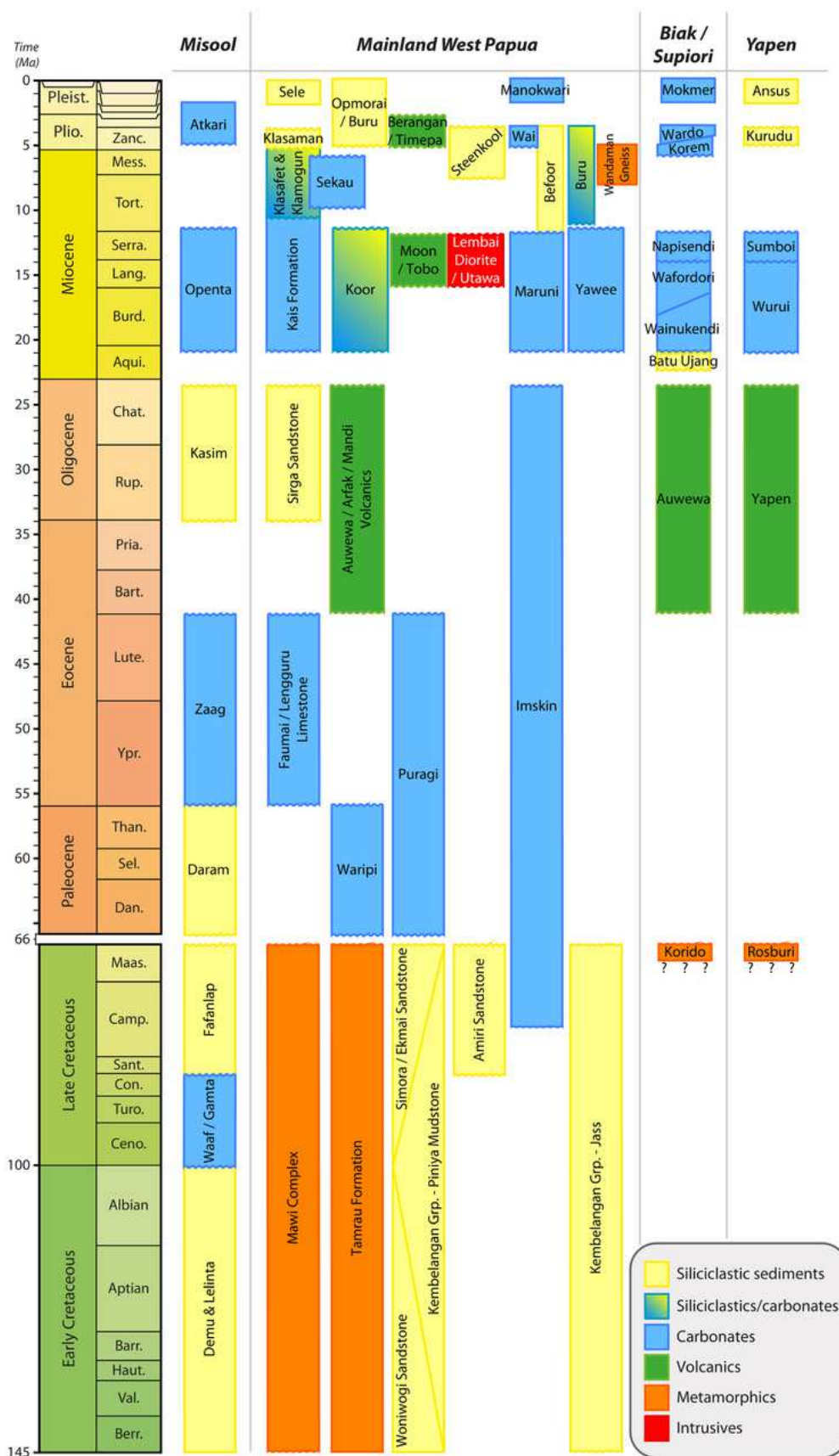


Figure 4.

## 2.1 Pacific Plate and contiguous stratigraphy

Within the intra-Pacific island arc, carbonate deposition was restricted to patch reefs developed around eroded volcanoes known from the Eocene age Auwewa Formation (Fig. 4). This persisted until the Oligocene–Early Miocene collision between an island arc and New Guinea (Wilson, 2002). Following collision, carbonate platform development was widespread across much of the Bird's Head Peninsula. Early to middle Miocene platform carbonates of the Kais and Maruni Limestones as well as the Wainukendi and Wafordori Formations (Figs. 2 and 4), were subsequently drowned during a middle to late Miocene transgressive event that abruptly terminated platform accumulation (Brash et al., 1991; Gold et al., 2014; Baillard et al., 2017). During the Pliocene, or very latest Miocene, rapid uplift attributed to major thrusting, folding (Wilson, 2002) and strike-slip faulting prevailed in the Bird's Head Peninsula, with the strike-slip faulting resulting in the formation of several sedimentary basins (Pieters et al., 1983). Areas that were uplifted due to collision eroded rapidly, filling these basins with siliciclastic sediment. Only the islands of Misool and Biak remained starved of siliciclastic sedimentation permitting deposition of platform carbonates of the Wardo, Korem and Mokmer Formations (Fig. 4) in relatively clear waters (Pieters et al., 1983; Wilson, 2002).

## **3. Methodology**

This paper presents the results of several field campaigns conducted by the Southeast Asia Research Group (SEARG), Royal Holloway University of London, in the Bird's Head Peninsula of Indonesian New Guinea between 2010 and 2016. Over these campaigns nearly 200 samples were collected from the New Guinea Limestone Group and other sedimentary units. These include a mixture of spot

samples as well as samples from logged stratigraphic sections (Supp. Data 1). All samples were thin sectioned and examined for petrography and biostratigraphic dating using planktonic and larger benthic foraminifera. Of these, 198 samples yielded well-constrained biostratigraphic ages (Supp. Data 1). Ages are assigned using planktonic foraminiferal zones of Blow (1979), Berggren and Miller (1988) and Berggren et al. (1995), recalibrated to Wade et al.'s (2010) sub-tropical planktonic foraminiferal zones. Larger benthic foraminiferal zones are assigned to the Indo-Pacific 'letter stages' of Adams (1965, 1970), later refined by BouDagher-Fadel (2008) and Lunt (2013). We subdivided the biostratigraphic results into 19 time intervals to show the palaeogeographic evolution of western New Guinea between the Carboniferous and Pleistocene.

Palaeogeographic reconstructions were determined using the bathymetric preferences of organisms (Hallock and Glenn, 1986; van Gorsel, 1988; Beavington-Penney and Racey, 2004; Murray, 2006; BouDagher-Fadel, 2008; 2015; Lunt, 2013) observed in each sample. The palaeogeographic maps presented here have been subdivided into five relative bathymetries according to the bathymetric preferences assigned to samples with depth-diagnostic foraminiferal assemblages (Fig. 5). Where heterogeneous depositional environments were interpreted at a single locality, the modal depositional setting for that time and location is recorded in the gross depositional maps.

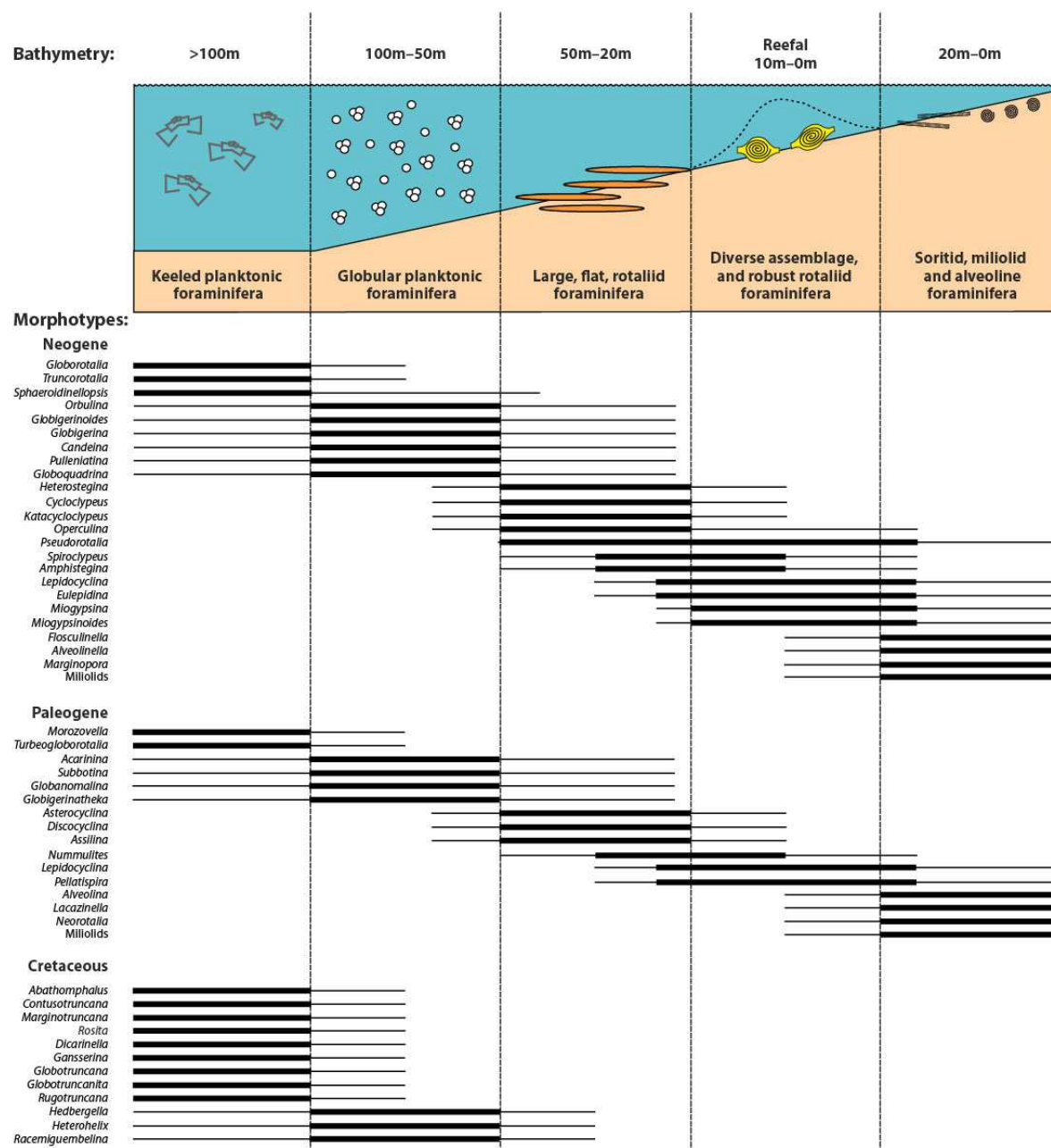


Figure 5.

In addition to the biostratigraphic ages and palaeoenvironments determined from our field studies, we also reinterpreted biostratigraphic and wireline log data, stratigraphic columns and existing palaeogeographic interpretations. This includes reinterpreting the regional stratigraphy of individual reef complexes within the Salawati and Bintuni basins as well as 136 public domain hydrocarbon exploration wells (Fig. 6 and Supp. Data 1). Stratigraphic intervals within the wells were

286 assigned to the relative bathymetry scheme using records of foraminiferal  
 287 occurrences that meet the criteria laid out in Figure 5.

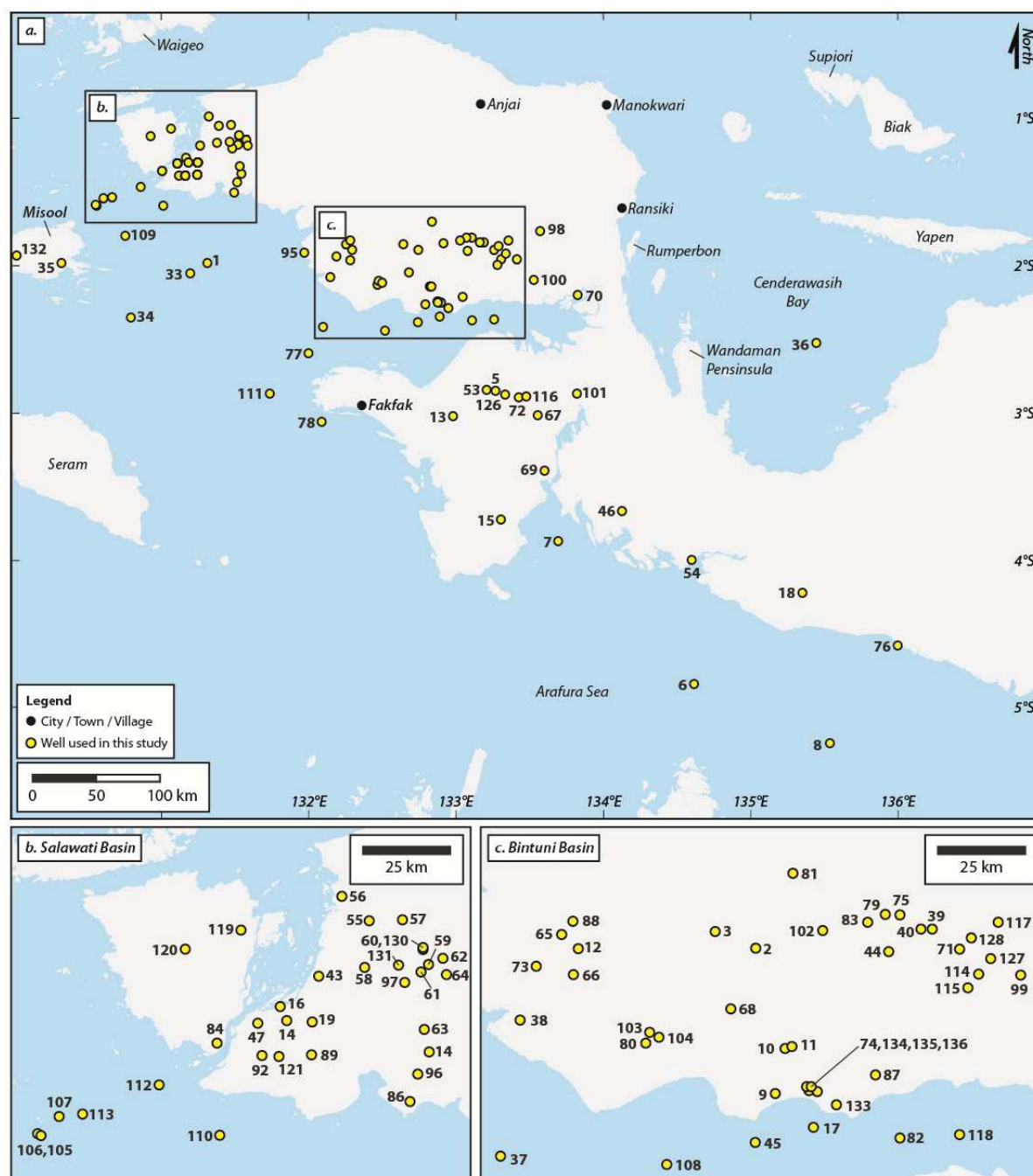


Figure 6

290  
 291 All of these data were used to produce a series of palaeogeographic maps. The  
 292 depositional bathymetries of samples and well intervals interpreted for each time  
 293 slice were plotted using ArcGIS so that the spatial distribution of facies could be

compared with existing palaeogeographic maps of the region (Visser and Hermes, 1962; Audley-Charles, 1965; 1966; Vincelette, 1973; Redmond and Koesoemadinata, 1976; Collins and Qureshi, 1977; Gibson-Robinson and Soedirdja, 1986; Brash et al., 1991; Norvick et al., 2003; Golonka, 2006; 2009). The new palaeogeographic maps were overlain on the present day configuration of western New Guinea (e.g. Visser and Hermes, 1962; Audley-Charles, 1965; 1966; Gibson-Robinson and Soedirdja, 1986; Brash et al., 1991) as most of New Guinea has been a part of the Australian plate for a considerable time, with minimal relative movement since at least the Permian (Audley-Charles, 1965; 1966; Gunawan et al., 2012; 2014). Consequently, we do not attempt the palinspastic restoration of structural features, such as the displacement of faults or large-scale rotation of crustal fragments, nor the restoration of plate fragments (e.g. Norvick et al., 2003; Golonka et al., 2006; 2009, Charlton, 2010; Hall, 2012). While the maps we developed are somewhat simplified in terms of the region's tectonic history, our aim was to produce a series of maps that could be used to identify the present day distribution of potential hydrocarbon plays and as an independent means to assess periodicity of localised tectonic driven uplift/subsidence events compared to global changes in sea level.

In addition to the paleogeographic maps, we also developed a regional relative sea-level curve for Western New Guinea for the Phanerozoic. This was produced by calculating the maximum, minimum and average bathymetry of all biostratigraphic control points (i.e. outcrop samples and well locations) analysed within a specific period of time. The "error bars" we report simply show the range of bathymetries within the time period. This regional relative sea-level curve was then compared to



global sea-level curves (e.g. Haq and Al-Qahtani, 2005; Müller et al., 2008; Snedden and Liu, 2010) to assess potential timing of tectonic events.

#### **4. Results and discussion of palaeogeographic reconstructions**

The following sections present the results of the palaeogeographic reconstructions and discuss how these maps compare to previously published work from similar studies. The data used to generate palaeogeographic reconstructions are listed in Supp. Data 1.

##### **4.1 Carboniferous**

Conglomerates, red beds and coal seams occur in many of the 14 study wells that intersect the formations of the Aifam Group (Fig. 3). This suggests the presence of widespread terrestrial depositional settings across the Bird's Head and Neck during the Carboniferous (Fig. 7; Pieters et al., 1983; Fraser et al., 1993; Norvick et al., 2003). Carboniferous corals observed from the Aifam Group in the central Bird's Head (Kato et al., 1999) and from outcrops of the Aiduna Formation (Martodjojo et al., 1975; Oliver Jr. et al., 1995) suggest the presence of shallow water, photic, settings surrounding the terrestrial zone.

The terrestrial zone is likely to have been associated with a magmatic arc considering the porphyritic volcanic rocks of the Melaiurna Granite dated by Bladon (1988) (Fig. 7a). If a magmatic arc was active at this time then it is likely that deeper water conditions could be found further to the north (Fig. 7). This subduction zone would have likely consisted of a ~southward-dipping (relative to the long-axis of the island), dehydrating, Proto-Pacific slab.

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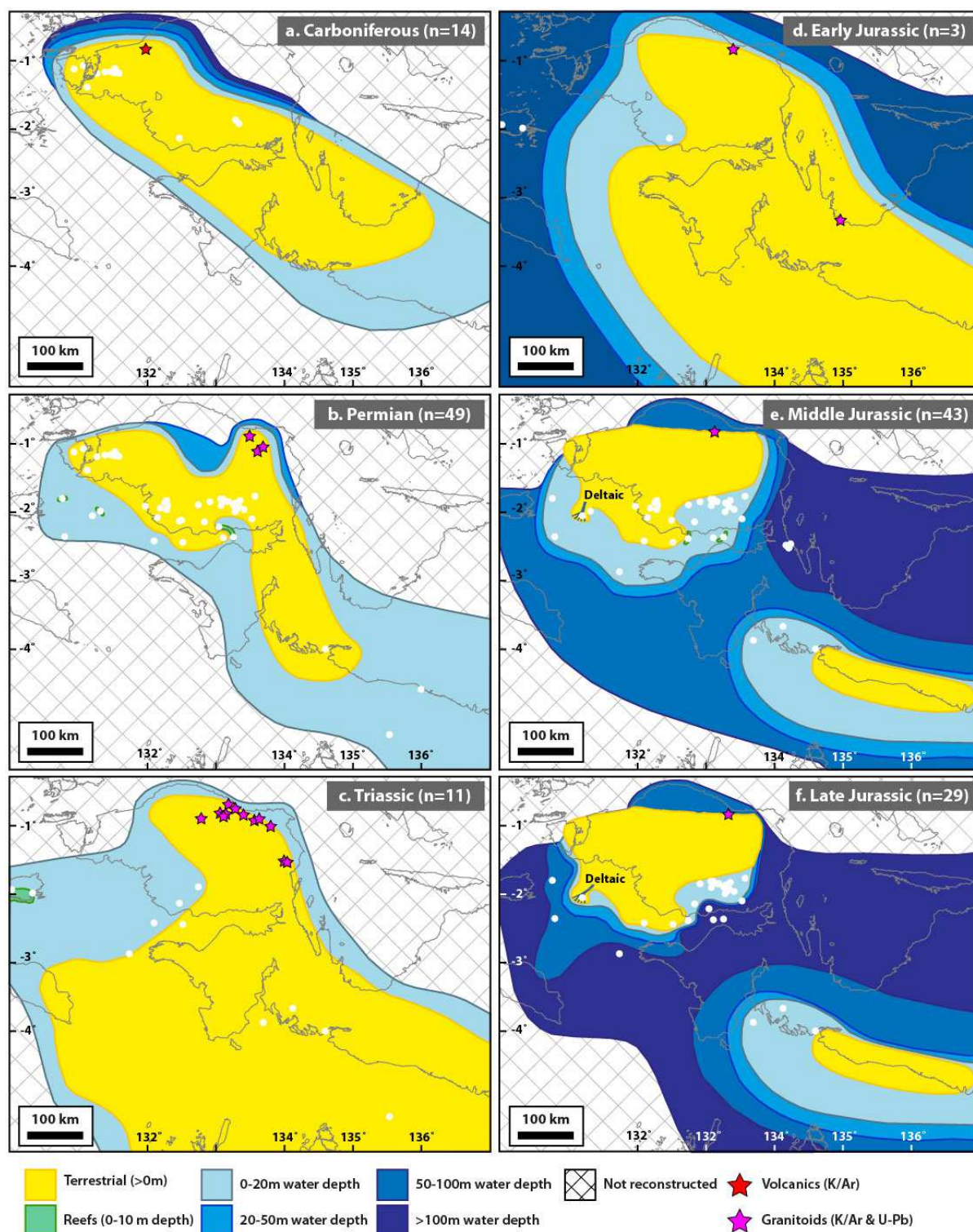


Figure 7.



## 4.2 Permian

Permian deposits of western New Guinea are distributed within a narrow terrestrial zone, extending across the central Bird's Head in the north and south- and westward into the Bird's Neck and Body (Fig. 7b). This terrestrial zone contains the land plants *Glossopteris* and *Gangamopteris* plants, reported to stretch from the West Papua to Papua New Guinea (Fontaine, 2001). Ten wells contain terrestrial deposits comprising combinations of red beds, coals, plants and freshwater palynomorphs. The Permian landmass of New Guinea was surrounded by shallow water units, interpreted to have been deposited in water depths no greater than 20m (Fig. 7b). Data from 13 wells record occurrences of delta front material and shallow water limestones with fusuline-algal assemblages similar to that of Ratburi Limestone in peninsular Thailand (Dawson, 1993; Fontaine, 2001). Deeper water settings are interpreted to the north of the landmass where low-energy, fine-grained siliciclastics and carbonates of the Ainim Formation and Aifat Mudstone outcrop.

## 4.3 Triassic

The only sedimentary unit in western New Guinea that is Triassic in age is the Tipuma Formation (Gunawan et al., 2012). These rocks were deposited within an arid continental setting comprising unfossiliferous red-bed sequences (Visser and Hermes, 1962; Pieters et al., 1983) and fluvial deposits (Gunawan et al., 2012; 2014). This is supported by the presence of oxidised sediments and continentally derived palynomorphs reported within many of the hydrocarbon exploration wells (Fig. 7c). Together, the field- and well data indicate that terrestrial deposition was widespread across much of western New Guinea (and Seram) during the Triassic (Fig. 7c). Other wells contain paralic and/or supralittoral sediments and are

interpreted here to represent shallow water deposits (<20m water depth). Triassic marine rocks are also reported from Misool (Pieters et al., 1983), including the presence of Norian age reefs (Fig. 7c; Van Bemmelen, 1949; Visser and Hermes, 1962; Audley-Charles, 1966). In addition, we also consider that an Andean-style magmatic arc extended along the length of New Guinea throughout the Triassic. This is based on igneous zircons within the fluvial sequences of the Tipuma Formation, as well as a belt of Triassic-aged granitoids that span the length of New Guinea and are interpreted to represent the uplifted magma chambers of the volcanic arc (e.g. Crowhurst et al., 2004; Gunawan et al., 2012; Webb and White 2016).

#### 4.4 Early Jurassic

The deposition of the Tipuma Formation continued until the Early Jurassic (Visser and Hermes, 1962; Pieters et al., 1983; Gunawan et al., 2012). Consequently, a narrow zone of terrestrial deposits is interpreted to extend from the Bird's Head, into the Bird's Neck and Bird's Body (Fig. 7d), and possibly farther into Australia and eastward along the Sula Spur. By the Early Jurassic open marine strata were being deposited on what is now the island of Misool (Visser and Hermes, 1962). Deep water clays and marls are also reported along the northern margin of a landmass extending from the Bird's Head and Neck, and centre of the Body (Audley-Charles, 1966; Norvick et al., 2003). Therefore, water depths between 50m and 100m are interpreted to surround the central New Guinea landmass (Fig. 7d).

#### 4.5 Middle Jurassic

The terrestrial deposition recorded over a ~28 Ma period during the Late Triassic to Early Jurassic was succeeded by deeper water sedimentation during a transgressive

event in the Middle Jurassic (Audley-Charles, 1966; Pieters et al., 1990; Lunt and Djaafar, 1991; Gunawan et al., 2012; Fig. 7e). This transgression likely led to the submergence of the Sula Spur. This increase in relative sea-level also reduced the land area of what is now western New Guinea, leading to the separation of the Bird's Head and Neck (Fig. 7e), as was proposed by Norvick et al. (2003). These newly formed islands were separated by a narrow 50m-100m deep seaway that accumulated shelfal clastic deposits (Fig. 7e). Deeper water settings are interpreted to have existed along the northern New Guinea margin, as supported by neritic clays found along today's northern coast – as was reported and proposed by Norvick et al. (2003).

Terrestrial deposits are interpreted from six wells in the central Bird's Head and southern Bird's Neck, based on the presence of continentally derived palynomorphs. A deltaic system to the west of the northern landmass (Fig. 7e) is recorded from the presence of fluvio-deltaic sediments within the CS-1X well as well as delta plain coals and organic claystones within the Inanwantan sequence (Fraser et al., 1993). These two islands were flanked by shallow seas with water depths no greater than 20m, according to sequences observed in 18 wells. Water depths in excess of 50m are delineated by outcrops of the Kopai Formation.

The Kopai Formation consists of deep-water black shales and limestones (Pieters et al., 1983). Black shales from the Kopai Formation contain a common 'Macrocephalites' ammonite assemblage close to the village of Wendesi. This assemblage includes typical North Gondwanan species including *Macrocephalites keeuwensis*, *Sphaeroceras boehmi* and *Holcophylloceras indicum* (Fig. 8). This

423 '*Macrocephalites*' ammonite assemblage is assigned a Bathonian-Callovian age  
424 (Westermann & Callomon, 1988; Westermann, 1992; Westermann, 2000; van  
425 Gorsel, 2012). These sequences were deposited within a distal, deep, open marine  
426 setting (van Gorsel, 2012). This interpretation is validated further by widespread  
427 evidence of Middle Jurassic belemnites in sequences in Papua New Guinea,  
428 Papua/West Papua, the Sula Islands and Misool (Challinor, 1990). Additional  
429 evidence for marine conditions is provided by various ammonites, bivalves and  
430 planktonic foraminifera from the Middle Jurassic Tamrau Formation, found in the  
431 northern-most Bird's Head (Pieters et al., 1983).



Figure 8.

Figure 7

#### 4.6 Late Jurassic

Continued regional transgression into the Late Jurassic saw the seaway between the two landmasses of the former Sula Spur attain water depths in excess of 100m (Fig. 7f). The deltaic system to the west of the northern landmass is interpreted to persist into the Late Jurassic due to the presence of sediments reported within the CS-1X well (Fig. 7f). Deep-water settings continued to encroach around the margins of the two western New Guinea islands throughout the Jurassic due to the continued rise in sea-level. These settings are delineated by outcrops of the Woniwogi, Kopai, Tamrau, Demu and Lelinta formations, interpreted as deep-water marine deposits (Pieters et al., 1983; Hasibuan, 1990). Wells that intersect Late Jurassic strata comprise glauconitic and argillaceous, fine-grained, distal sediments and bathyal agglutinated foraminifera such as *Glomospira* spp, and *Trochammina* spp.

#### 4.7 Early Cretaceous

By the Early Cretaceous, formerly subaerially exposed regions of western New Guinea were totally submerged beneath water depths in excess of 100m (Fig. 9a). This is supported by the presence of widespread deep marine deposits of the Piniya Mudstone and Woniwogi Formation across the central Bird's Head (Pieters et al., 1983). Widespread deep water sedimentation is also supported by ammonites and belemnites within the Kembelangan-1 well (Visser and Hermes, 1962) and carinate Globotruncanid planktonic foraminifera, such as *Praeglobotruncana* spp., *Paraglobotruncana* spp. and *Rotalipora* spp., in the Kembelangan-1 well. A bathymetric gradient shallows towards the south-west with interpreted water depths between 50m and 100m (Fig. 9a). This is based on the presence of shelfal agglutinated and calcareous benthic foraminifera, such as *Lenticulina* spp., and

sediments dominated by globular planktonic foraminifera including *Hedbergella* spp.,  
*Heterohelix* spp. and *Ticinella* spp. Additional support for this is based on a lack of  
carinate foraminifera within wells along the southern New Guinea margin.

Although the Woniwogi Formation is assigned a Late Jurassic to Early Cretaceous  
age (Pieters et al., 1983), the planktonic foraminifera listed above (recorded from the  
Woniwogi Formation in the Kembelangan-1 well) indicate a restricted late Early  
Cretaceous, Aptian-Albian, age.



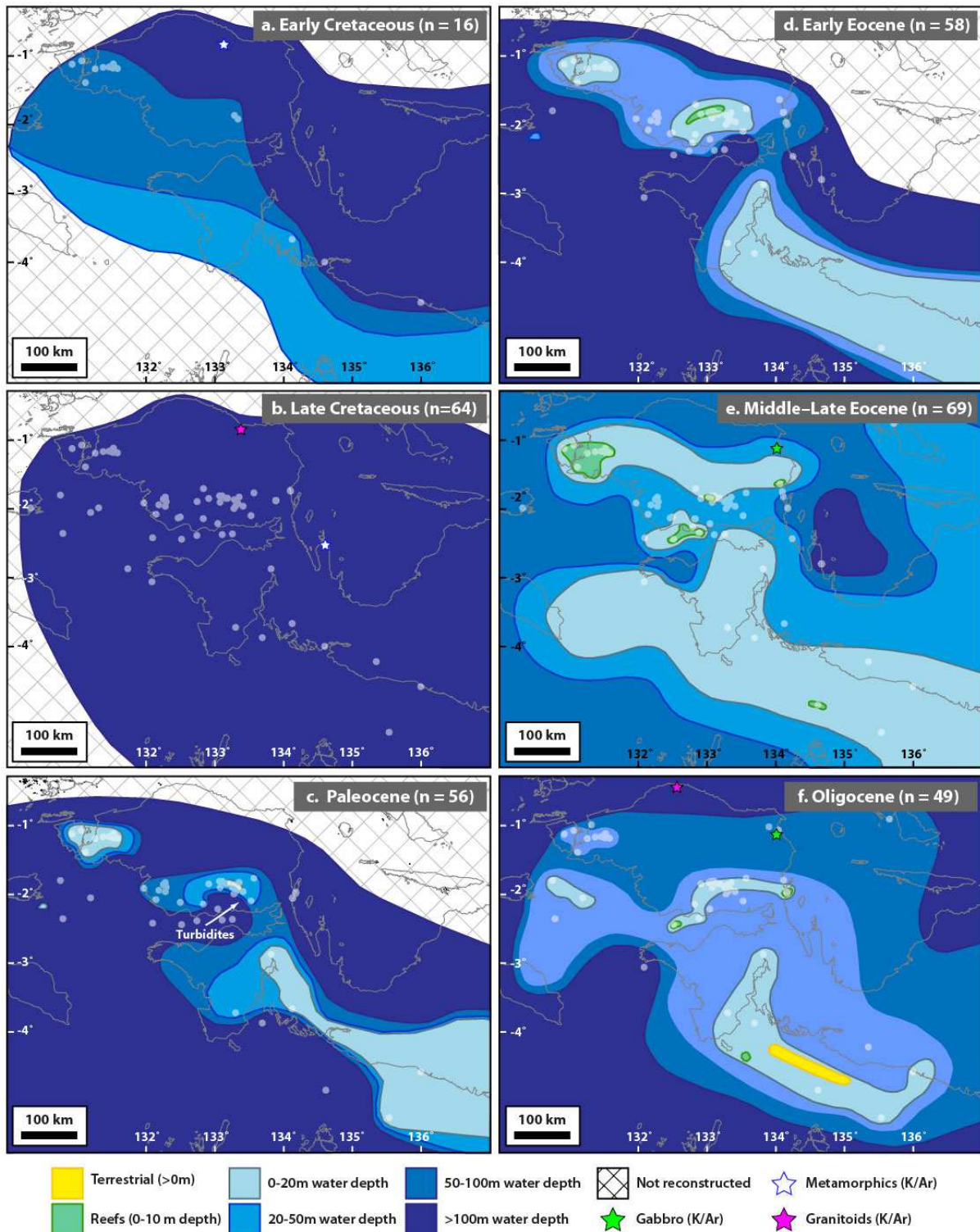


Figure 9.

#### 4.8 Late Cretaceous

Relative sea-level rise reached its peak during the Late Cretaceous where water depths in excess of 100m are interpreted across much of western New Guinea (Fig.



9b). Many of the 58 reviewed wells contain diagnostic deep-water taxa, dominated by carinate globotruncanid planktonic foraminifera including, but not exclusively, *Abathomphalus mayaroensis*, *Dicarinella* spp., *Gansserina gansseri*, *Globotruncana aegyptiaca*, *Globotruncana arca*, *Globotruncana linneiana*, *Globotruncana ventricosa*, *Globotruncanita* spp., *Globotruncanita stuartiformis*, *Helvetoglobotruncana helvetica*, *Marginotruncana* spp., *Rosita* spp., *Rosita fornicata*, *Rotalipora* spp., *Rugoglobotruncana* spp., *Whiteinella* spp., *Whiteinella archeocretacea*, and globular planktonic foraminifera including *Heterohelix* spp., *Pseudoguembelina* spp. and *Racemiguembelina fructicosa*. Campanian to Maastrichtian age sediments were collected during field work from the Imskin Limestone in the south-east of the Bird's Head (Fig. 9b). Six samples contain deep-water taxa, indicative of outer neritic to lower bathyal water depths (>100m). These include including *Abathomphalus mayaroensis*, *Contusotruncana fornicata*, *C. plummerae*, *Gansserina gansseri*, *Globotruncana arca*, *Globotruncana bulloides*, *Globotruncana linneiana*, *Globotruncanita conica*, *Globotruncanita. stuarti*, *Rugotruncana subcircumnodifer* and *Heterohelix globulus* (Fig. 10). The abundance of these carinate planktonic foraminifera in both wells and outcrop samples indicate deposition within an upper bathyal setting, in water depths in excess of 300m.

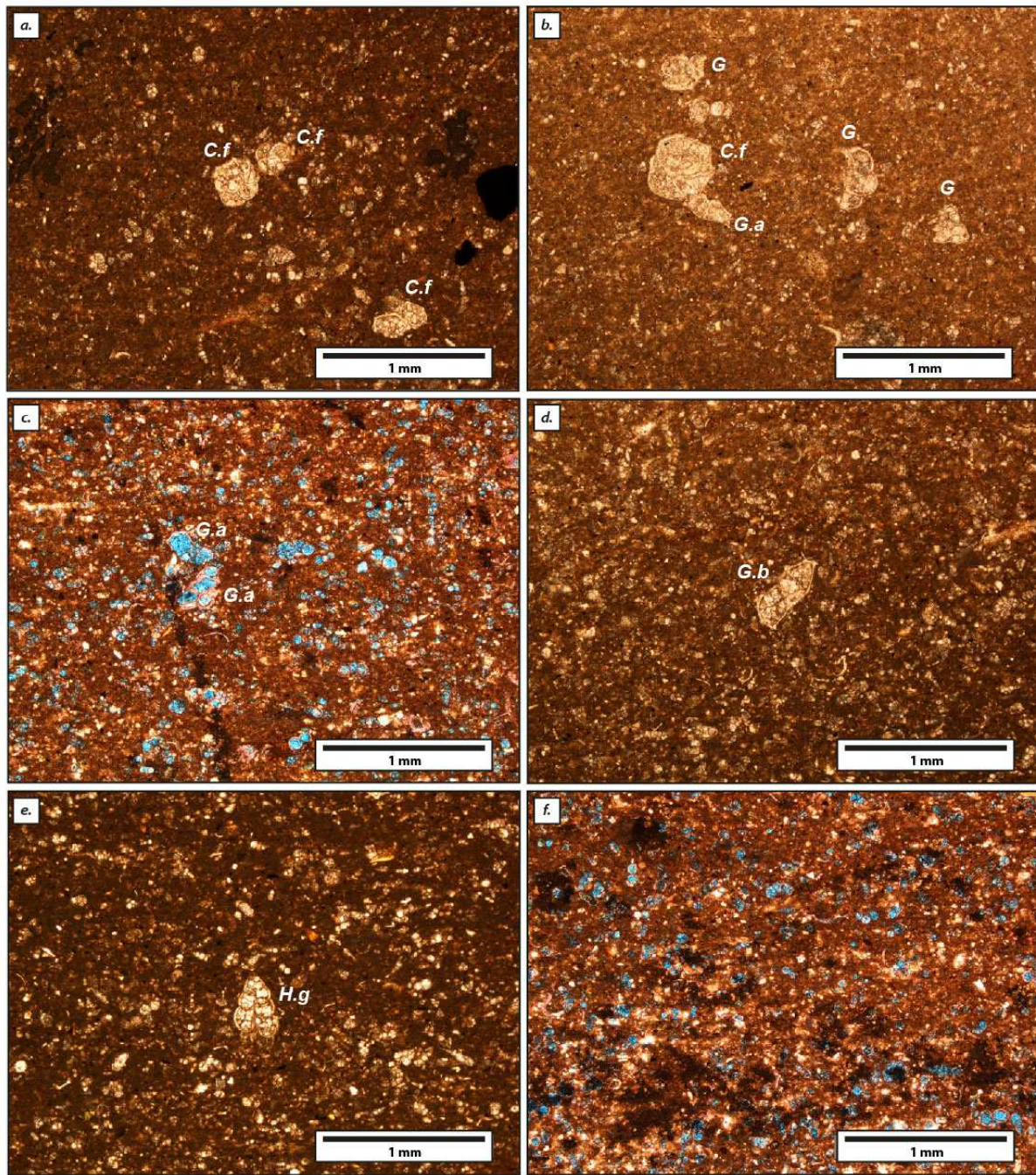


Figure 10.

#### 4.9 Paleocene

Following the Late Cretaceous relative sea-level high, water levels receded during the Paleocene, particularly around the southern Bird's Head, Neck and Body (Fig. 9c). The distribution of shallow water (<20m) areas is delineated by the outcrop distribution of the Waripi Formation and where these sequences were intersected in



wells, particularly in the southern Bird's Body (Fig. 9c). The Waripi Formation consists of a shallow-water limestone containing abundant oolites, miliolids and bryozoa (Visser and Hermes, 1962; Brash et al., 1991). Farther north, particularly within the Bintuni Basin and offshore to the west, deeper waters in excess of 100m are encountered in many wells. These wells contain Daram Formation turbiditic material and carbonate mudstones comprising carinate and globular foraminifera. Foraminifera include *Morozovella* spp., *M. acuta*, *M. aequa*, *M. angulata*, *M. edgari*, *M. inconstans*, *M. pseudobulloides*, *M. velascoensis*, *Acarinina* spp., *Eugubina* spp., *Globanomalina* spp. and *Subbotina* spp. We interpret that the Daram turbidites in the central Bird's Head were deposited from east to west along strike of a narrow submarine canyon opening towards the west (Fig. 9c). An exception to this trend is provided by sandstones from the Daram Formation that outcrop on Misool. These sequences contain the larger benthic foraminifera *Lockhartia* and *Discocyclina* which indicate water depths between 20m and 50m during Paleocene to Early Eocene (Belford, 1991).

Five samples collected from the Imskin Limestone near Rumberpon Island were dated to be Paleocene age. All samples are interpreted to have been deposited in an outer neritic to lower bathyal setting where water depths exceed 100m (Fig. 9c). These samples contain a planktonic foraminiferal assemblage comprising globular and carinate morphologies including *Acarinina coalingensis*, *A. primitiva*, *Globanomalina imitata*, *G. ovalis*, *Morozovella aequa*, *M. angulata*, *M. conicotruncata*, *Subbotina* spp. and *Turbeogloborotalia compressa*.

#### 4.10 Early Eocene

Relative sea-level fall continued into the Early Eocene and more shallow water areas developed within the central Bird's Head (Fig. 9d). The Faumai Limestone contains shallow water carbonate bank and shoal deposits and reefal facies (Pieters et al., 1983). This is supported by well data where shallow water areas up to 20m in depth are interpreted north of the Bintuni Basin in the southern Bird's Neck and Body based on the presence of alveolinids including *Lacazinella* spp. and *Fasciolites* spp. Moderate water depths between 20m and 50m are interpreted from the Faumai Limestone of several wells and outcrop samples that contain alveolinids as well as abundant large, flat, rotaliine foraminifera such as *Assilina* spp., *Cycloclypeus* spp., *Discocyclina* spp. and *Operculina* spp. Pieters et al. (1983) proposed that the Faumai Limestone was deposited between the Middle Eocene and Oligocene. However, the presence of alveolinids including *Alveolina globosa*, *A. laxa*, *A. moussoulensis* and *A. subpyrenaica*, and larger benthics including *Asterocyclina* spp., *Discocyclina ranikotensis*, *Cuvillierina* spp. and *Daviesina* spp. (Fig. 11) indicate that the Faumai Limestone must have to be as old as the Early Eocene (Ypresian), correlating to planktonic foraminiferal zone E1 and Indo-Pacific letter stage 'Ta2' (Fig. 4).

Deeper water areas are interpreted to persist in the wells of the Bintuni Basin, from outcrop samples collected close to Rumberpon Island and from limestone clasts extracted from a Pleistocene conglomerate collected on the east coast of the Wandaman Peninsula (Fig. 9d). The Bintuni wells contain mixtures of Early Eocene globular and carinate planktonic foraminifera including *Morozovella* spp., *M. aragonensis*, *M. formosa*, *M. quetra*, *M. subbotinae*, *Acarinina* spp., *Acarinina nitida*

551 and *Subbotina* spp. Rocks collected from the Imskin Limestone and Early Eocene  
552 age clasts within the Pleistocene conglomerate from the Wandaman Peninsula also  
553 suggest water depths greater than 100m during the Early Eocene (Fig. 9d). Samples  
554 collected from these localities contain the planktonic foraminifera *Acarinina* spp.,  
555 *Acarinina bulbrooki*, *A. decepta*, *Globigerina lozanoi*, *Globigerinatheka* spp.,  
556 *Morozovella formosa*, *M. lensiformis*, *M. subbotinae* and *Subbotina* spp (Fig. 11).  
557



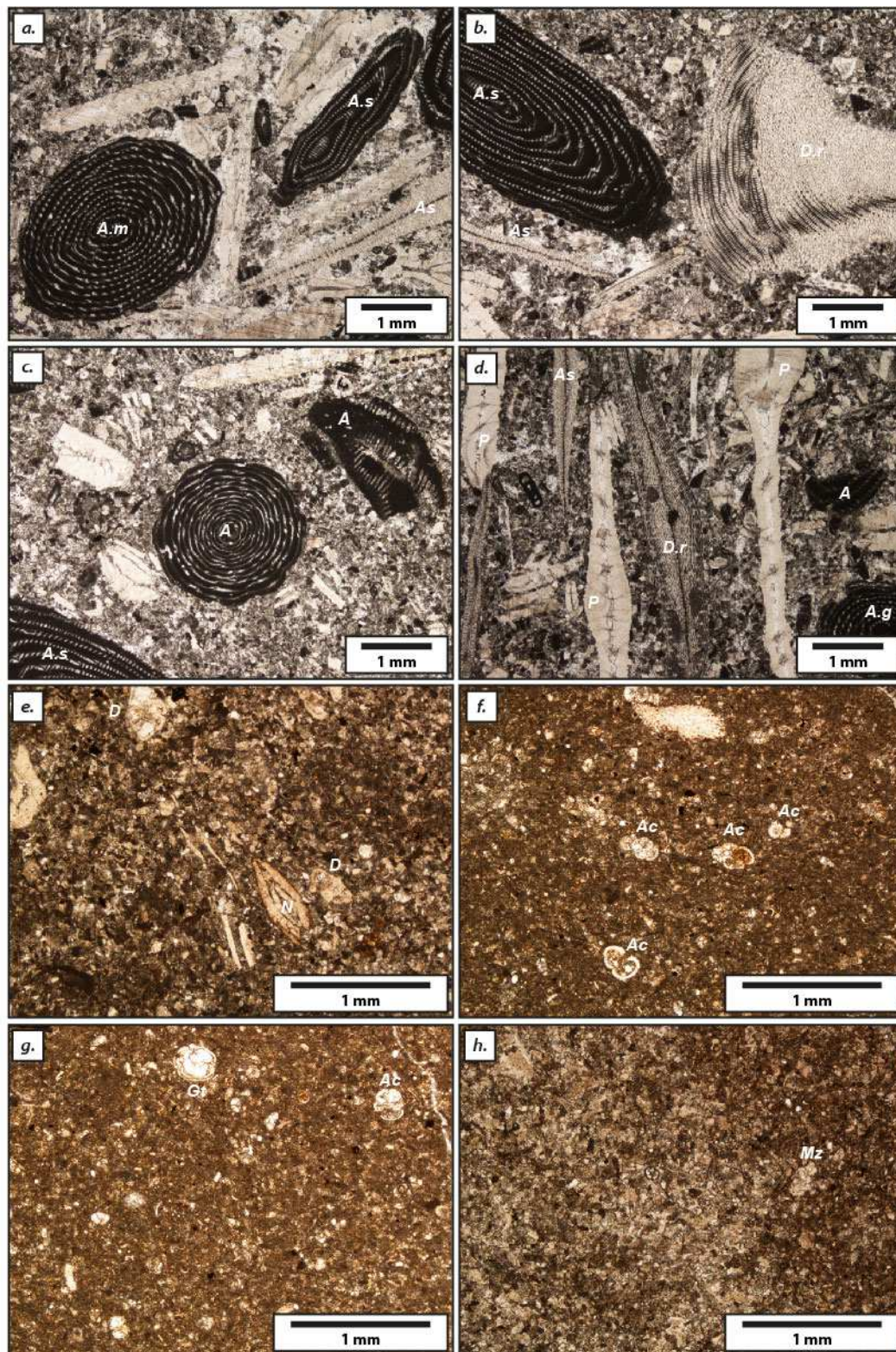


Figure 11.

#### 4.11 Middle - Late Eocene

The lowest Paleogene relative sea-level occurred across much of western New Guinea during the Middle to Late Eocene (Fig. 9e). Shallow water areas were prevalent across the central Bird's Head and Seram, and extended along the southern Bird's Neck and Body (Fig. 9e). These shallow waters are indicated by limestones dominated by *Alveolina* and *Lacazinella* (Visser and Hermes, 1962), while deeper water deposition around the Bird's Neck is indicated by planktonic foraminifera collected from limestone clasts within a Plio-Pleistocene conglomerate exposure (Fig. 9e).

Well data indicate the presence of shallow waters no greater than 20m depth punctuated by isolated reefal build-ups across most of the central Bird's Head Peninsula (Fig. 9e). This is primarily based on the presence of shallow water and reef-loving taxa such as *Alveolina* spp., *Fasciolites* spp., *Lacazinella wichmanni*, *Nummulites* spp., *Nummulites djodjarkartae* and *Pararotalia* spp. as well as corals observed within the ASA-1X, Aum-1, Boka-1X, Rawarra-1, Sago-1, Sebyar-1 and TBE-1X wells. Bathymetric gradients away from the shallow water platforms approach 50m (Fig. 9e) where large flat rotaliines including *Assilina* spp., *Discocyclus* spp., *Heterostegina* spp., *Operculina* spp. and assemblages of small calcareous benthic foraminifera typical of shelf settings are found in wells East Misool-1, Soeaboar-1, Steenkool-1 and Tarof-2. Deeper water (50-100m) facies are interpreted in the Onin exploration wells based on the presence of *Acarinina* spp., *Globigerinatheka* spp. and *Morozovella* spp.



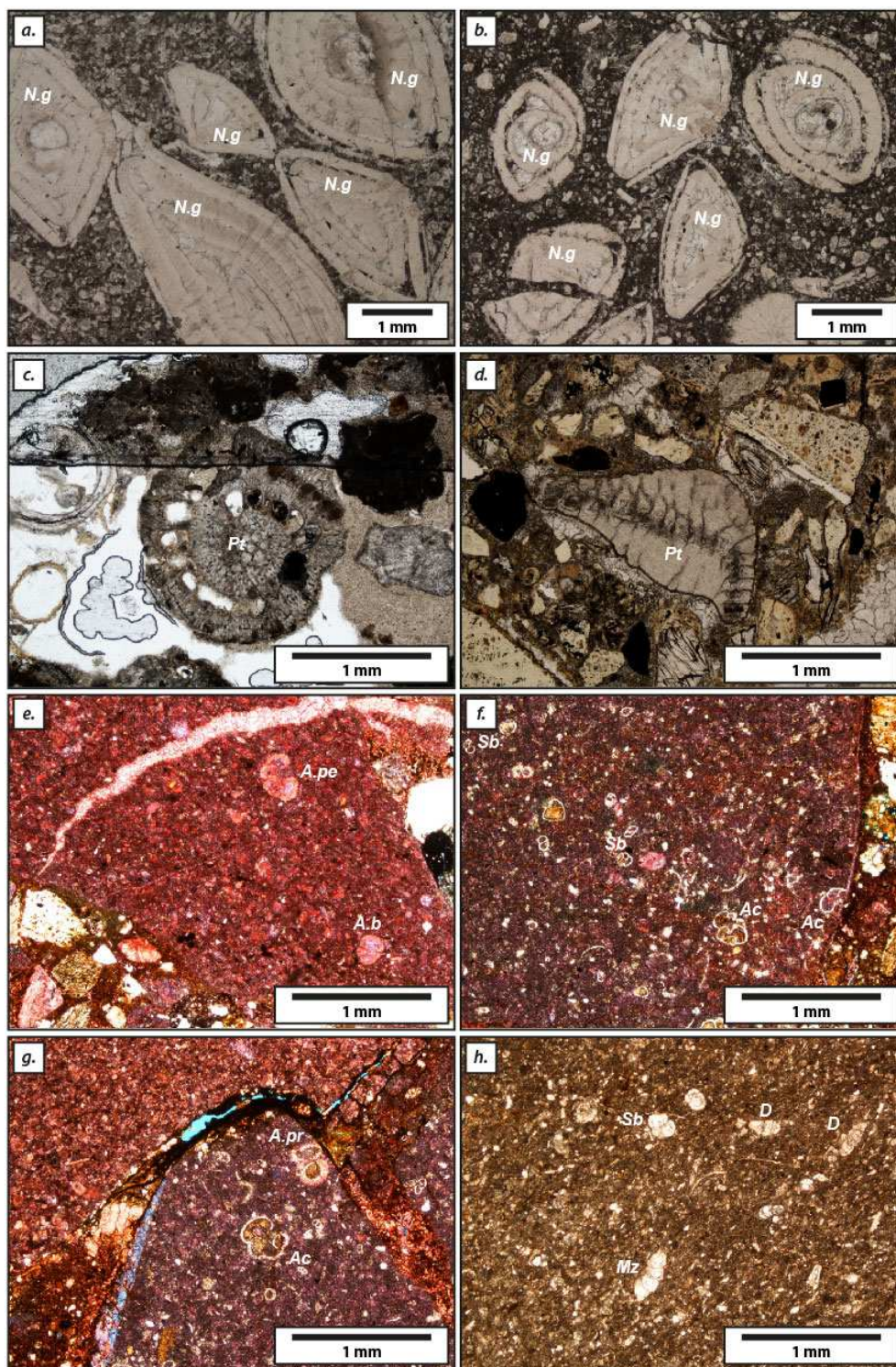
Interpretations of biostratigraphic data within the exploration wells are supported by outcrop evidence along the western coastline of Cenderawasih Bay. Close to the village of Ransiki, shallow water facies include grainstones containing large *Alveolina elliptica* and *Nummulites gizehensis* within samples of the Faumai Limestone (Fig. 12). Farther to the south-east of Ransiki, samples contain large flat rothliines including *Assilina exponens*, *Asterocyclina* sp. and *Discocyclina sella* indicative of moderate water depths. Water depths between 50m and 100m are interpreted close to Rumberpon Island (Fig. 9e), where rocks of the Imskin Limestone contain the planktonic foraminifera *Acarinina intermedia*, *Globigerina tripartita*, *Porticulasphaera mexicana* and *Subbotina* spp. Parts of the Imskin Limestone (including transported clasts within a conglomerate on the Wandaman Peninsula) indicate outer neritic water depths in excess of 100m around the Wandaman Peninsula region. Samples here contain a mixture of globular planktonic foraminifera including *Acarinina bullbrooki*, *A. decepta*, *A. pentacamerata*, *A. primitiva*, *A. pseudotopilensis*, *Globigerinatheka* sp., *Subbotina eocaenica* and carinate forms including *Morozovella aragonensis* and *M. crassata* (Fig. 12).

The oldest foraminifera observed on the islands of Biak and Supiori are *Pellatispira* sp. These are an exclusively Late Eocene (Priabonian) aged genus indicative of Indo-Pacific 'letter stage' Tb (Adams, 1970; Figs. 4 & 12). These larger benthic foraminifera are found reworked within clasts of Auwewa Formation material within the Batu Ujang Conglomerate outcropping around Wafordori Bay on the north coast of Supiori. Although reworked, *Pellatispira* sp. signify moderate water depths up to several 10's of metres within the vicinity of Supiori. This taxon is also observed within the Auwewa Formation encountered in wells in the Mamberamo region (located in



610 the northern section of the Bird's Body, east of Yapen Island – this falls outside of  
 611 the boundary of the maps presented in Figs. 1, 2, 7, 9).

612



613

614

Figure 12.

#### 4.12 Oligocene

Relative sea-level rose across parts of western New Guinea during the Oligocene. Despite this, a narrow terrestrial area developed to the south of the Bird's Neck (Brash et al., 1991; Norvick et al., 2003), with deeper waters found to the northeast and west (Fig. 9f). This narrow island was surrounded by shallow bodies of water, denoted by the presence of *Austrotrillina* spp. in several wells including ASA-1X, ASF-1X and ASM-1X (Fig. 9f). Occasional reefal build-ups are interpreted farther north where *Nummulites* spp are recorded from TBE-1X (Fig. 9f). Water depths up to 50m, around the southern Bird's Head and Neck (Fig. 9f), are indicated by the presence of larger benthic foraminifera including *Cycloclypeus* spp., *Heterostegina borneensis*, *Operculina* spp. and *Pararotalia* spp. Moderate water depths are also interpreted in the Salawati Basin, primarily from well reports of *Heterostegina borneensis* (Visser and Hermes, 1962). Deeper water areas (Fig. 9f) occurred where Oligocene aged rocks, including those of the Sirga Formation, are dominated by intermediate water depth taxa such as *Catapsydrax* spp., *Globigerina ampliapertura*, *Globoturborotalita ouachitaensis*, *Paragloborotalia opima* recorded within the Klalin-1, and Onin South-1X wells.

Six samples of Early and Late Oligocene age were collected from the west coast of Cenderawasih Bay (Fig. 9f). Shallow water reef front facies (<10m water depth) were found near Rumberpon Island where samples contain specimens of *Neorotalia* sp. and one of the last species of *Nummulites*, *N. fichteli* (BouDagher-Fadel, 2008). Late Oligocene rocks were also observed in sedimentary lenses of the Arfak Volcanics of the eastern Bird's Head and Auwewa Formation on Supiori (Fig. 9f). These samples

consist of planktonic foraminiferal packstones and wackestones indicating outer slope depths between 50m and 100m. Planktonic foraminifera of 'intermediate-water' depths consist of globular morphologies including *Globigerina gortanii*, *Globigerina praebulloides*, *Globigerinoides primordius* and *Globoquadrina binaiensis*. However, these are found east of the Ransiki Fault (Fig. 2) and may indicate deeper water depths away from the current setting and juxtaposed against more shallow water rocks through movement along this fault.

#### 4.13 Oligocene-Miocene

Towards the end of the Oligocene and beginning of the Miocene arc-continent collision resulted in folding and thrusting of intra-Pacific island arc material as it was accreted to the Australian continent (e.g. Davies et al., 1996; Hall, 2002; Wilson, 2002; Hill and Hall, 2003; Gold et al., 2014). Much of this material was exposed with up to 820m of section being lost due to sub-aerial erosion. This is marked by a widespread angular unconformity (Gold et al., 2014) identified in several wells to the west of the Bird's Head Peninsula as well and as far as the eastern margin of Cenderawasih Bay (Fig. 13a).



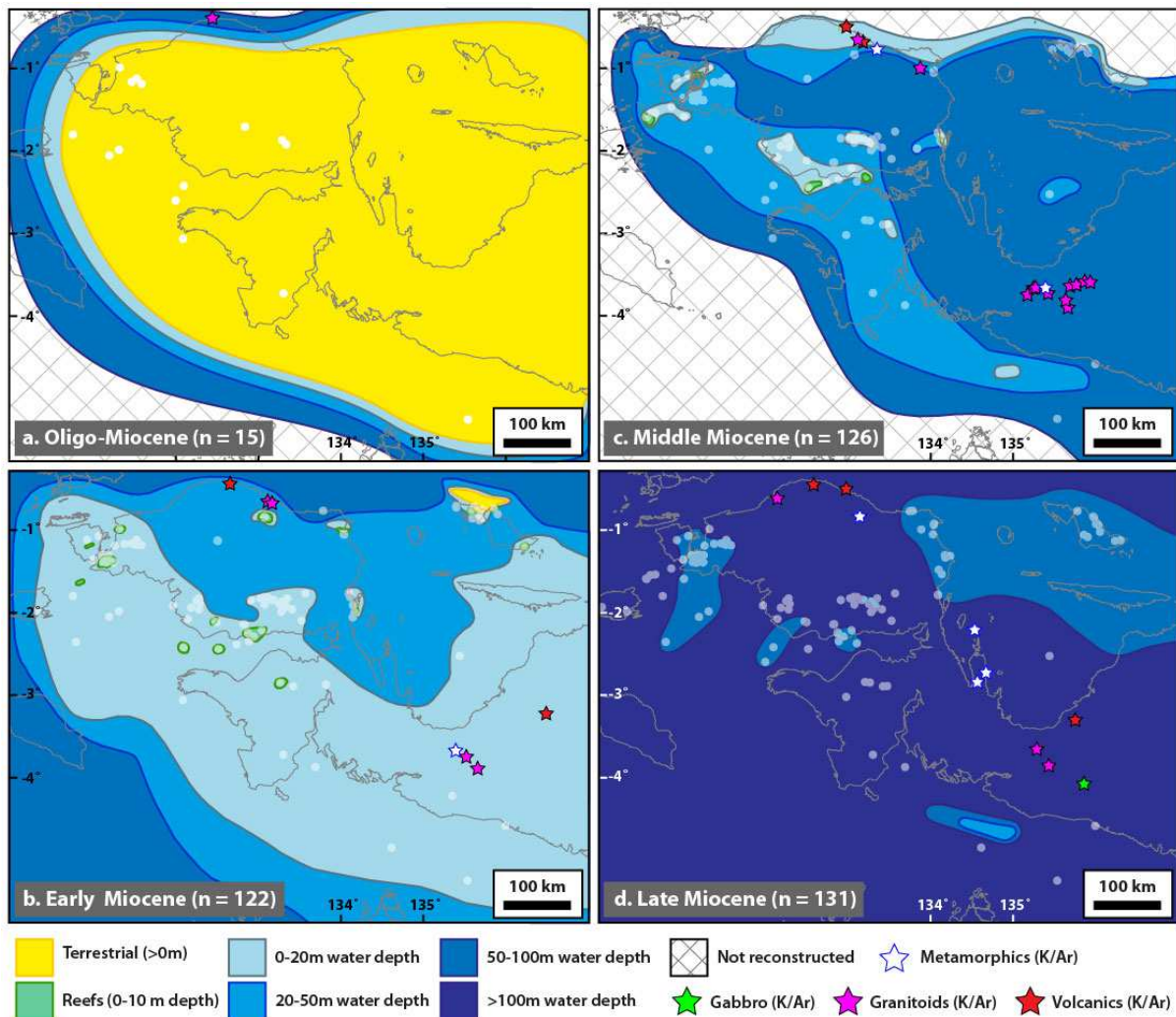


Figure 13.

#### 4.14 Early Miocene

The Early Miocene saw the presence of widespread shallow water carbonate platforms across western New Guinea and Cenderawasih Bay, with maximum water depths no greater than 50m (Fig. 13b). Early Miocene aged units of the New Guinea Limestone Group including the Kais, Koor and Maruni limestones on the Bird's Head Peninsula, the Wurui Limestone of Yapen, and Wainukendi and Wafordori formations of Biak and Supiori. These consist of predominantly shallow water to reefal carbonates (Visser and Hermes, 1962; Pieters et al., 1983; Brash et al., 1991). These units were mapped without distinction between shallow and relatively deeper

water facies; therefore the distribution of these formations is used only to interpret water depths no greater than 50m (Fig. 13b), thus accommodating potential heterogeneity within the New Guinea Limestone Group.

The region was dominantly covered by shallow water during the Early Miocene – dominated by reefs and carbonate platforms (Fig. 13b). These carbonates have abundant larger benthic foraminifera and they occur across much of western New Guinea, including carbonate build-ups and patch-reefs in the Salawati Basin (Gibson-Robinson and Soedirdja, 1986).

A broad platform populated by reefal build-ups extending from the western Bird's Head to the Bird's Body (Fig. 13b) was interpreted from 85 wells. These wells intersect packstones, grainstones and reefal rudstones and floatstones that contain shallow water taxa including *Alveolinella praequoyi*, *Amphistegina* spp., *Austrotrillina* spp., *Borelis* spp., *Flosculinella* spp., *Lepidocyclina* spp., miliolids, *Miogypsina* spp., *Miogypsinoidea* spp., *Spiroclypeus* spp. and other organisms such as sponges, coral, echinoids and bivalves. This platform was surrounded by a body of water no greater than 50m in depth (Fig. 13b) indicated by the presence of the larger benthic foraminifera *Operculina* spp., *Heterostegina* spp. and *Cycloclypeus* spp. Rare deeper water sediments of this age also occur in Seram where they contain the globular planktonic foraminifera *Globigerinoides* spp., *Globigerina* spp. and *Catapsydrax* spp.

In outcrop, many reefal carbonates can be seen at the base of the Kais and Maruni Limestones of the mainland and Wainukendi Formation of Biak and Supiori. These

reefs are mapped isolated patch reefs (Fig. 13b), although their lateral extent is unknown. Reefal carbonates and those deposited in moderate water depths contain an abundant and diverse fossil assemblage, predominantly comprising larger benthic foraminifera: *Eulepidina badjirraensis*, *Lepidocyclina* (*Nephrolepidina*) *brouweri*, *L. (N.) isolepidinoides*, *L. (N.) nephrolepidinoides*, *L. (N.) oneatensis*, *L. (N.) stratifera*, *L. (N.) sumatrensis*, *Heterostegina borneensis*, *Miogypsina intermedia*, *M. kotoi*, *M. tani*, *Miogypsinoides bantamensis*, *Mdes. dehaarti*, *Miogypsinodella primitiva*, *Miolepidocyclina*, *Operculina* sp. and *Spiroclypeus tidoenganensis* (Fig. 14).



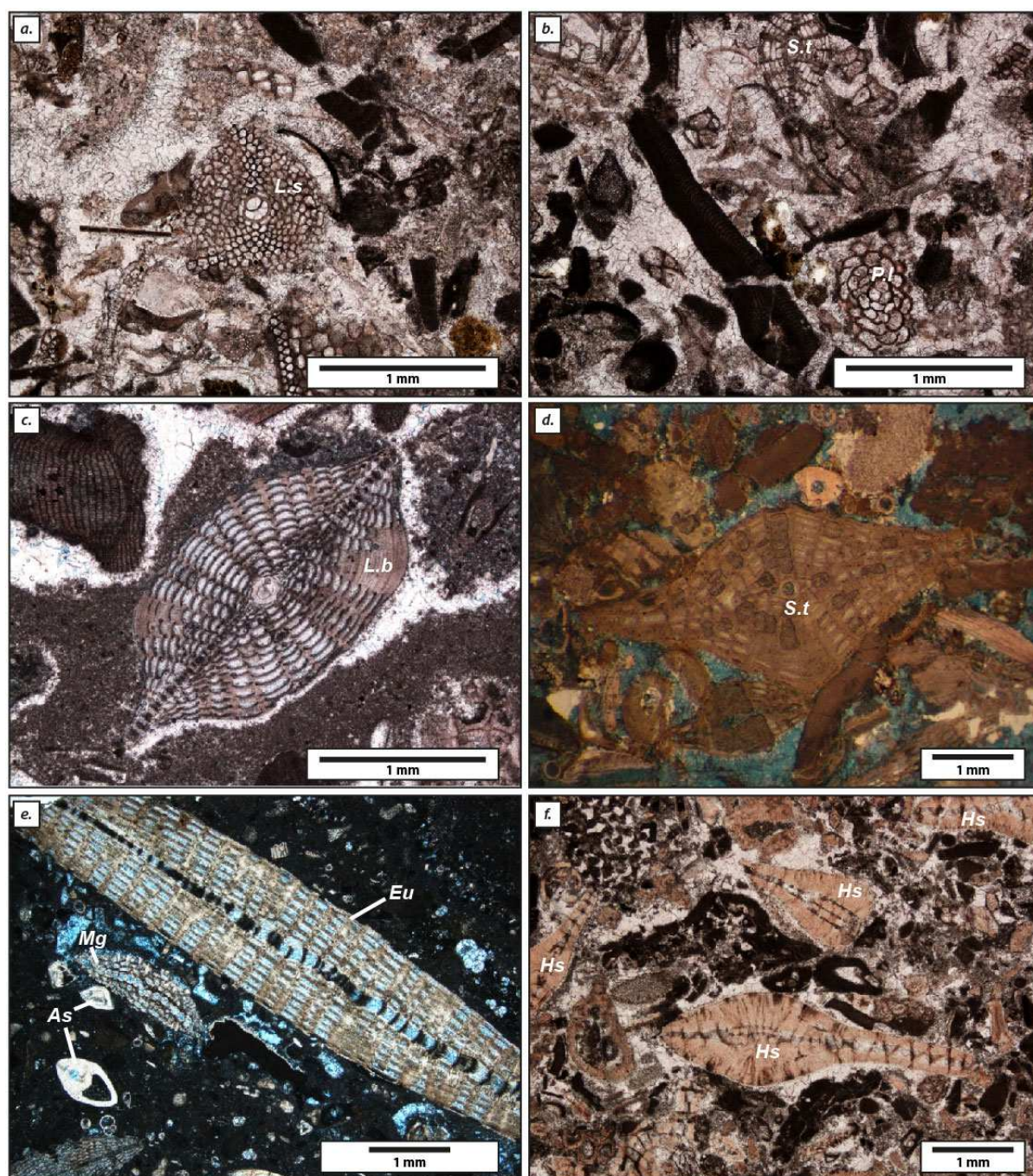


Figure 14

#### 4.15 Middle Miocene

A regional transgressive event initiated in the Burdigalian so that by the Middle Miocene much of western New Guinea was submerged in water up to 100m depth (Fig. 13c) (e.g. Brash et al. 1991). Evidence for a rise in relative sea-level can be found in deep water facies of the Napisendi Formation and Sumboi Marl found on

the islands within Cenderawasih Bay, as well as in the drowning successions at the top Maruni and Kais Limestone (Gold et al., 2014).

Early Miocene shallow water carbonate platforms were replaced by more moderate water depths in the Salawati and Bintuni basins, and areas south of the Bird's Head Peninsula. At the same time, there is pronounced backstepping to shallow water regions to the north-east of the island of Supiori (Fig. 13c).

A narrow moderate water depth carbonate platform developed on western and southern margin of Bird's Head Peninsula and the Bird's Neck (Fig. 13c). This broadly supports Brash et al.'s (1991) interpretation of platform carbonate in the southern margin of the Lengguru Fold and Thrust Belt and pelagic carbonates to the northeast.

Taxa indicative of moderate water depths, including *Cycloclypeus* spp., *Operculina* spp., and *Pseudorotalia* spp., are prevalent in 18 wells distributed across western New Guinea (Fig. 13c). Isolated carbonate platforms and occasional pinnacle reefs are recorded in the main basins of the Bird's Head Peninsula which contain the shallow water taxa *Alveolinella quoyi*, *Flosculinella bontangensis*, *Lepidocyclina* (N.) spp., *Marginopora vertebralis*, *Miogypsina* spp. as well as corals, red algae, bivalves and echinoids. Deeper water areas are interpreted from the presence of planktonic foraminiferal assemblages including the taxa: *Orbulina universa*, *Globigerina druryi*, *Globigerinoides subquadratus*, *Globigerinoides diminutus*, *Globigerinoides bisphaericus*, *Praeorbulina glomerosa*, *Praeorbulina transitoria*, *Paragloborotalia siakensis*, *Globorotalia fohsi*.

Outcrop samples of shallow water deposits from the Koor Formation in the northern Bird's Head Peninsula include soritid foraminifera (e.g. *Marginopora vertebralis*) and miliolids including *Quinqueloculina* spp. and *Alveolinella quoyi*. These sequences are also found on Biak where they are interbedded within the Napisendi Formation. An isolated reef is interpreted near Rumberpon Island at this time (Fig. 13c) – samples from this area contain reef-loving organisms such as miogypsinid and lepidocyclinid larger benthic foraminifera.

Deep water deposits occur in the upper parts of the Kais and Maruni limestones and Napisendi Formation, extending south to the central Bird's Head and Cenderawasih Bay (Fig. 13c). These samples contain abundant globular planktonic foraminifera that indicate intermediate water depths between 50m and 100m. Examples include *Orbulina suturalis*, *O. universa*, and many species of *Globigerinoides* including *G. quadrilobatus*, *G. trilobus*, and rare *Globorotalia* spp. (Fig. 15). Other outcrop samples from the Kais and Maruni Limestones of the Bird's Head Peninsula and the Wafordori Formation on Biak contain large flat rotaline foraminifera including *Katacycloclypeus annulatus* and *Cycloclypeus carpenteri*, lepidocyclinids including *Lepidocyclina* (N.) *brouweri*, *L. (N.) ferreroi*, *L. (N.) omphalus*, *L. (N.) verbeeki*, miogypsinids including *Miogypsinoides indica*, *Miogypsina cushmani*, *M. intermedia*, *M. kotoi*, *M. regularia* (Fig. 15).



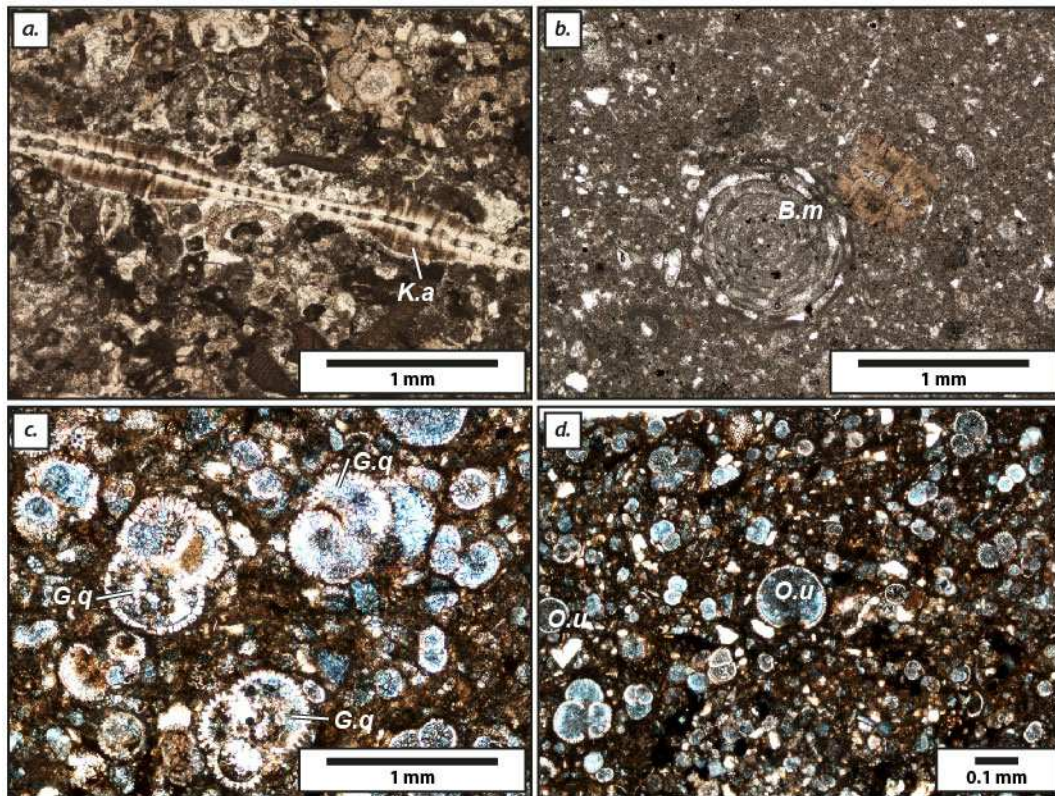


Figure 15.

#### 4.16 Late Miocene

Relative sea-level continued to rise during the Late Miocene so that water depths greater than 100m were widespread across much of western New Guinea (Fig. 13d). Visser and Hermes (1962) and Golonka et al. (2006, 2009) interpret deep water facies rocks, represented by the Befoor and Klasafet Formations of the Bird's Head and Neck, to indicate greater deep-water deposition across much of the region. Small reefal areas are present during this time, but cover much smaller areas than those seen during the Early Miocene (e.g. Visser and Hermes 1962). However, wireline logs from exploration wells indicate these areas were probably deposited in slightly deeper water, particularly in the Salawati and Bintuni basins, as has been recognised in several other studies (Vincelette 1973; Redmond and Koesoemadinata 1976; Collins and Qureshi 1977; Gibson-Robinson and Soedirdja 1986). We also

take the Kais Limestones to be Early to Middle Miocene in age, rather than these being as young as Late Miocene as per Norvick et al. (2003). This discrepancy can explain why we do not show a widespread shallow water carbonate platform through the centre of the Bird's Head and Neck in the Late Miocene (e.g. Norvick et al., 2003).

Evidence for the prevalence of water depths between 50m and 100m in the eastern Bird's Head and islands to the north of Cenderawasih Bay come from the abundance of 'intermediate-water' species including *Candeina nitida* and *Orbulina suturalis* (Bé, 1977) found within the outcrop samples we examined. Farther south, in samples collected close to Rumberpon Island (Fig. 13d), water depths in excess of 100m are interpreted from abundant carinate planktonic foraminifera (e.g. *Globorotalia plesiotumida*, *Truncorotalia ronda*) and the thick-walled globular planktonics (e.g. *Sphaeroidinellopsis subdehiscens* and *Globoquadrina dehiscens*). These water depths are interpreted from wells in the Salawati and Bintuni basins as well as within the Arafura Sea, due to the presence of thick-walled and carinate planktonic foraminifera mentioned above as well as *Dentoglobigerina baroemoensis*, *Globorotalia merotumida*, *Neogloboquadrina acostaensis*, *Neogloboquadrina humerosa* and *Sphaeroidinellopsis* spp.

#### 4.17 Early Pliocene

The Early Pliocene consisted of dominantly open marine settings across western New Guinea during the Early Pliocene (Fig. 16a). Water depths in excess of 50m are recorded from wells across western New Guinea that contain microfossils assemblages dominated by globular and carinate planktonic foraminifera including

*Globigerina* spp., *Globigerinoides* spp., *Globorotalia* spp., *Neogloboquadrina* spp.,  
*Sphaeroidinella* spp. and *Sphaeroidinellopsis* spp.

Relatively shallower water facies are recorded in wells to the south and west of the  
 Bird's Head (Fig. 16a). This includes shallow water facies such as grainstones, coral  
 floatstones and back-reef lagoonal wackestones that contain the taxa *Ammonia* spp.,  
*Amphistegina lessonii*, *Calcarina spengleri*, *Heterostegina* spp., *Marginopora* spp.,  
*Neorotalia calcar*, *Pararotalia* spp., *Peneroplis* spp., *Pseudorotalia* spp. and miliolids.

Outcrop samples collected from the Befoor and Klasaman formations in the eastern  
 Bird's Head contain abundant globular planktonic foraminifera (e.g. many species of  
*Globigerinoides* spp., *Neogloboquadrina* spp., *Pulleniatina* spp., *Sphaeroidinella* spp.  
 and *Sphaeroidinellopsis* spp., as well as *Orbulina universa*). Carinate planktonic  
 foraminifera such as species of *Globorotalia* spp. are interpreted to have been  
 washed into this environment and large flat benthic foraminifera such as *Operculina*  
 spp. are interpreted to have been transported down slope. To the north-east of the  
 Bird's Head, evidence for shallower reefal settings occur within reef front facies rocks  
 of the Wai Limestone containing *Calcarina spengleri*, *Amphistegina* spp. and  
 abundant rodophyte red algae deposited in front of back-reef facies units (Fig. 16a).  
 Shallow water facies, interpreted as back-reef lagoons, to the east of the Bird's Head  
 (Fig. 16a) contain soritid foraminifera including *Marginopora vertebralis*, small  
 rotaliids including *Quasirotalia guamensis*. Delicate corals and the dasycladacean  
 green alga, *Halimeda* are also found in the Early Pliocene specimens.



On the islands of Biak and Supiori, a small bathymetric high is interpreted to pass quickly from inner slope sediments into outer neritic settings, with steeply inclined slopes found around the peak (Fig. 16a). Outer neritic sediments representing water depths in excess of 100m occur towards the Biak Basin to the south-west. These sediments contain common carinate planktonic foraminifera including *Globorotalia conoidea*, *G. margaritae*, *G. menardii*, *G. miocenica*, *G. tumida*, *G. sphericomiozea*, *Truncorotalia crassula* and the thick walled globular planktonic foraminifera *Sphaeroidinellopsis seminulina*. Carinate planktonic foraminifera observed in the Korem and Wardo formations are indicative of >100m water depths.

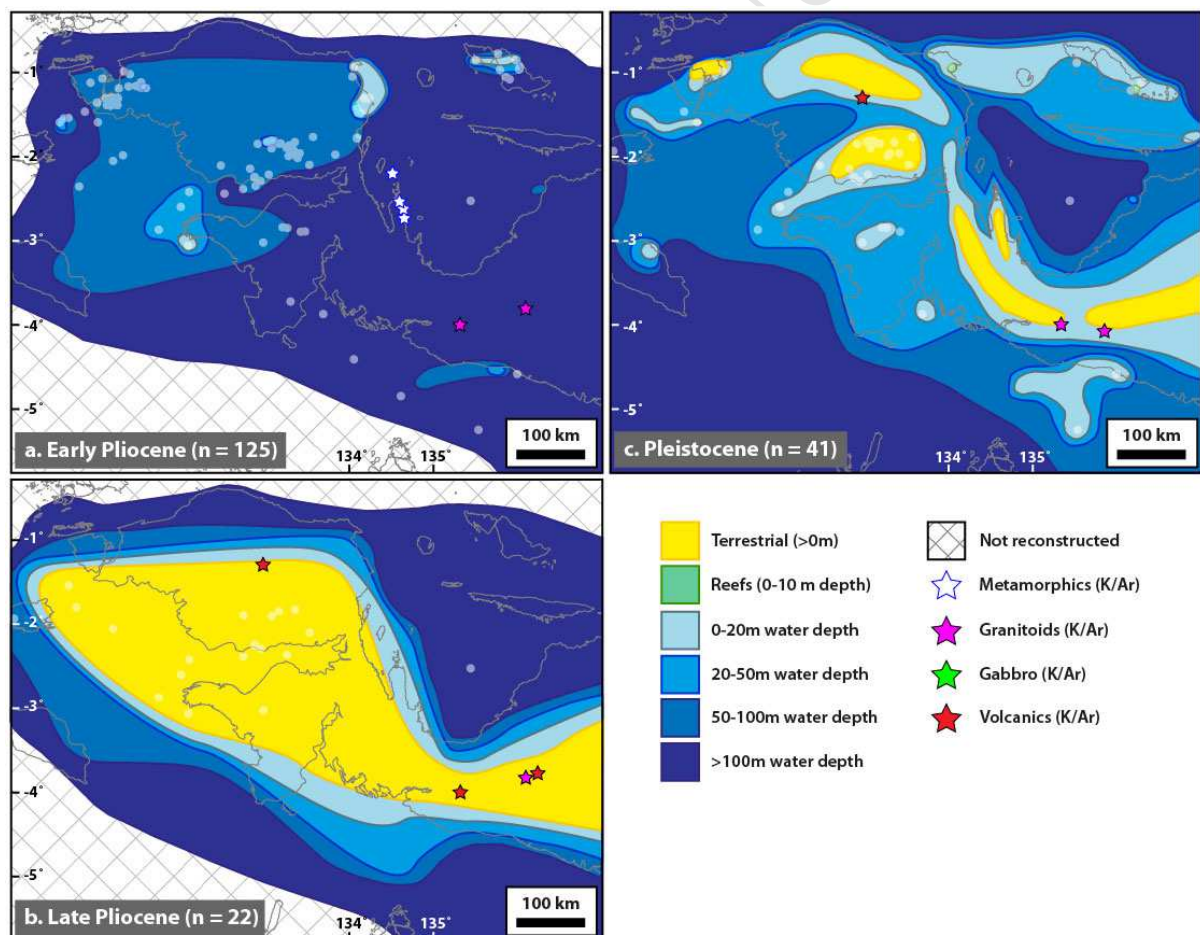


Figure 16.

#### 4.18 Late Pliocene

Sea-level regression occurred in western New Guinea towards the end of the Early Pliocene, resulting in extensive shallow water areas especially to the west of the Bird's Head Peninsula (Fig. 16b). This emergent area is responsible for the formation of the regional intra-Pliocene unconformity of Pairault et al. (2003) and Decker et al. (2009).

Deep water areas are interpreted based on the presence of globular and carinate planktonic foraminifera including *Globigerina* spp., *Globigerinoides* spp., *Globorotalia* spp., *Neogloboquadrina* spp., *Sphaeroidinella* spp. and *Sphaeroidinellopsis* spp. The distribution of relatively shallower areas are interpreted based on the presence of large flat rotaliines including *Cycloclypeus*, *Heterostegina* spp., *Operculina* spp. and typical back reef or lagoonal taxa such as soritid and miliolid foraminifera, coral, echinoids and bivalves.

#### 4.19 Pleistocene

The relative fall in sea-level that commenced in the Late Pliocene continued into the Pleistocene and through to the present day in western New Guinea. Several areas of the Bird's Head, Neck and Body were submerged beneath waters no greater than 50m and localised areas were subaerially exposed close to the Salawati and Bintuni basins (Fig. 16c) as a precursor to the present day topography of New Guinea.

The islands found to the north of Cenderawasih Bay (e.g. Biak, Yapen, Supiori) record carbonate platform deposition in shallow water as well as reefal facies and sedimentary breccia (e.g. the Mokmer and Manokwari formations) (Fig. 16c). This deposition was largely coeval with the deposition of the Ansus Conglomerate on

Yapen, which may indicate that parts of this island were subaerially exposed During the Pleistocene. The northern most sub-basins in Cenderawasih Bay became much deeper during this period and these are interpreted to be filled by pelagic carbonates comprising planktonic foraminiferal packstones (Fig. 16c).

Palaeogeographic interpretations suggest a southwest directed deepening trend across a broad carbonate platform no deeper than 50m in water into the much deeper setting of Cenderawasih Bay (Fig. 16c). The presence of a carbonate platform attaining these moderate water depths is indicated by common occurrences of the larger benthic foraminifera *Heterostegina* spp., and globular planktonic foraminifera including *Pulleniatina obliquiloculata* and *Globigerinoides quadrilobatus*. Rocks interpreted to have been deposited in reefal, shallow water settings up to 10m in depth comprise grainstones that contain abundant encrusting rodophyte red algae resilient to the brunt of high hydrodynamic energies. Behind this, quiet waters of the back-reef are situated to the east of the island and contain delicate bryozoa and branching corals of the genera *Acropora* and *Porites*. Dasycladacean green algae, such as *Halimeda*, are also common. The disintegration of algal needles may contribute towards the large amount of micrite in wackestones deposited in this setting.

## 5. Discussion

### 5.1 Comparisons with previous palaeogeographic reconstructions

Our paleogeographic reconstructions broadly support the previously published works of Visser and Hermes (1962), Audley-Charles (1965; 1966), Vincelette (1973), Redmond and Koesoemadinata (1976), Collins and Qureshi (1977), Gibson-

Robinson and Soedirdja (1986), Brash et al. (1991), Norvick et al. (2003) and Golonka (2006; 2009). However, there are a number of notable differences, which we suspect are largely driven by access to additional data, as well as a thorough, consistent re-interpretation of regional biostratigraphic data. We summarise the main differences between our work and earlier interpretations in the following sections.

### *5.1.1 Paleozoic*

Visser and Hermes (1962) interpret paralic sediments across much of western New Guinea during the Permo-Carboniferous (Fig. 7a-b). We interpret that terrestrial environments were more prevalent during the Carboniferous with increasing marine influence developing in the early Permian. Our interpretation of broadly terrestrial settings during the Carboniferous is in contrast to the interpretation of Golonka et al. (2006), who propose a deep-water slope setting along the northern margin of New Guinea during this time. Visser and Hermes (1962) and Pieters et al. (1983) suggest that the Aiduna Formation is the southerly equivalent to the 'C' Member of the Aifam Group to which they assign a Permian age. However, Martodjojo et al. (1975) and Oliver Jr. et al. (1995) separate the Aiduna Formation as a distinct lithological unit and assign a Carboniferous age based on biostratigraphy of the rugose corals. We favoured the biostratigraphic interpretation of Martodjojo et al. (1975) and Oliver Jr. et al. (1995) for the age of this unit. In addition, we extend the Permian landmass of Audley-Charles (1965) farther north. This is based on Permian terrestrial sediments recorded from new wells drilled in this region north after 1965.

## 5.1.2 Mesozoic

Evidence from outcrop and well data also push the Australian-New Guinea landmass and paralic sediments of Audley-Charles (1966) farther north so that much of western New Guinea is emergent during the Triassic (Fig. 7c). This supports palaeogeographic maps of Visser and Hermes (1962) and Norvick et al. (2003) who proposed land extended from the central Bird's Head, Neck and southern margin of the Bird's Body (Fig. 7c). These interpretations contrast with Audley-Charles' (1966) position of northern New Guinea within a deep water setting at this time.

Our reconstructions extend the deep-water settings of Audley-Charles (1966) along the central spine of New Guinea during the Late Jurassic. By the Early Cretaceous deep-water settings are interpreted across much of the Bird's Head. This differs from Norvick et al. (2003) who place an isolated landmass within the central Bird's Head at this time.

Widespread open marine and bathyal facies across western New Guinea during the Late Cretaceous support interpretations of Visser and Hermes (1962), Audley Charles (1966), Brash et al., (1991) and Norvick et al. (2003). However, Brash et al., (1991) and Norvick et al. (2003) indicate that the late Campanian Ekmai sandstones of the Bird's Neck were deposited in shallow water. This is based on the presence of larger benthic foraminifera *Lepidorbitoides* and *Pseudorbitoides* found within the sandstones (Visser and Hermes, 1962). We speculate that the juxtaposition of Late Cretaceous deep- and shallow-water facies may be associated with shortening of the Lengguru Fold and Thrust Belt.



### 5.1.3 Cenozoic

The Paleocene landmass of Norvick et al. (2003) in the Bird's Head is hereby reinterpreted as an isolated shallow water region. This is based on evidence from oolitic and bioclastic shoal limestones within the Waripi Formation of the Salawati Basin.

Our reconstructions broadly support the Early Eocene interpretation of Brash et al. (1991) and Golonka et al. (2009) which show pelagic carbonate deposition in the Bird's Neck. This interpretation is supported by carinate planktonic foraminifera observed in outcrop samples from this region. By the Middle to Late Eocene, we have interpreted widespread shallow water carbonate deposition across the majority of western New Guinea, much like the earlier maps of Visser and Hermes (1962), Norvick et al. (2003) and Golonka et al. (2009). Our reconstructions refine Visser and Hermes' (1962) palaeogeographic interpretation of open marine facies close to the Fakfak region of the Bird's Head Peninsula as well as near the Wandaman Peninsula (Fig. 9e).

The Oligocene reconstructions are broadly similar to those of Brash et al. (1991) and Norvick et al. (2003), showing a terrestrial area in the southern Bird's Neck deepening towards the northeast. Norvick et al. (2003) interpret the central Bird's Head to be emergent at this time, although evidence from outcrop samples indicates shallow water deposition was occurring in this region (Fig. 9f). This was also recognised by Golonka et al. (2006; 2009).

## 5.2 Temporal Trends

A first-order highstand sea-level occurred during the Silurian (Ross & Ross, 1988; Golonka, 2006), but relative sea-level fell between the Silurian and Devonian. The conditions changed, with deep water deposition being replaced by dominantly terrestrial environments which persisted between the Permian and Early Jurassic (Fig. 17). Transgression throughout the Middle Jurassic and into the Cretaceous resulted in peak Mesozoic relative sea-level by the Late Cretaceous (Fig. 17). This period corresponds with a time of maximum global sea-levels during the Phanerozoic (Golonka et al., 2006), and the deposition of many fine-grained siliciclastic formations. Relative sea-level dropped during the Paleogene until the Middle to Late Eocene when widespread shallow water areas permitted the growth of extensive carbonate platforms represented by the oldest units of the New Guinea Limestone Group. This includes the Faumai, Lengguru and Imskin limestones as well as carbonate lenses within the Auwewa Formation.

Relative sea-level increased for a short duration during the Oligocene before the onset and perpetuation of arc-continent collision between the Australian and Pacific Plates between the Oligocene and Early Miocene (e.g. Davies et al., 1996; Hall, 2002; Hill and Hall, 2003). This collision caused sub-aerial erosion of Paleogene sediments in some areas forming a regional Oligocene-Miocene unconformity (Gold et al, 2014; Fig. 13a). This uplift is also recognised as widespread carbonate platform growth and deposition of Early Miocene units of the New Guinea Limestone Group in other areas.

Stable shallow-water carbonate deposition of the New Guinea Limestone Group continued for at least 6 Ma across much of western New Guinea until a second regional transgressive event initiated in the Burdigalian (Fig. 17). Relative sea-level rise reached its peak in the Late Miocene, possibly correlating with the global Tor1 flooding event (Hardenbol, 1998; Gradstein et al., 2012; Baillard et al., 2017), resulting in the deposition of widespread deep-water limestones and fine-grained siliciclastics of the Klasafet and Klasaman formations (Fig. 17). We also speculate that this may have been related to a phase of crustal extension associated with the metamorphic core complexes exposed on the Wandaman Peninsula (e.g. Bailly et al., 2009; François et al., 2016). Relative sea-level began to fall again during the Pliocene (Fig. 17), culminating in short-lived sub-aerial exposure of an area to the west of the Bird's Head forming a regional intra-Pliocene unconformity (Pairault et al. 2003; Decker et al. 2009).

The regional Bird's Head relative sea-level curve is similar to that of published global sea-level curves (Haq and Al-Qahtani, 2005; Müller et al., 2008; Snedden and Liu, 2010) from the Silurian to Paleocene (Fig. 17). This implies that the primary control on relative sea-level change throughout this time is eustatic. However, there are disparities between the regional and global sea-level curves from the Early Eocene to Oligocene (Fig. 17). This suggests that the primary control on relative sea-level change is more localised at this time and may be attributed to tectonic effects of regional subsidence and uplift and/or environmental controls influencing sedimentation rates. Following arc-continent collision in the Early Miocene the regional relative sea-level curve of western New Guinea returns to recording the signal of global eustatic sea-level change (Fig. 17).

### 5.3 Comparisons with computer models

Our palaeogeographic reconstructions broadly support, and build upon, previously published palaeogeographic maps of New Guinea based on empirical data (e.g. Visser and Hermes, 1962; Audley-Charles, 1965; 1966; Brash et al., 1991; Golonka, 2006; 2009) but differ to computer modelled global and regional palaeogeographies (e.g. Zahirovic, 2014; 2016, Heine et al., 2015; Leprieur et al., 2016). Most of these models use global eustatic sea-level curves (Haq et al., 1987; 2014, Haq and Al-Qahtani, 2005; Haq and Shutter, 2008; Müller, 2008; Snedden and Liu, 2010, Miller et al., 2011) as a basic parameter, applying a particular sea-level curve(s) to regional basins, including those in Southeast Asia. The sea-level curves of Haq et al. (1987) and Haq and Al-Qahtani (2005), in particular, are based on observations from the Arabian platform which has been a relatively stable homoclinal carbonate ramp since the Paleozoic (Haq and Al-Qahtani, 2005). This region therefore preserves a good record of facies changes up and down the ramp enabling the determination of past regional sea-level change. Active plate margins however are less stable, which is perhaps why we record different palaeogeographic histories to the more automated/data mining approaches employed in some of the numerical models generated for New Guinea (e.g. Zahirovic, 2014; 2016, Heine et al., 2015; Leprieur et al., 2016).

Heine et al (2015) concluded that calculations of land areas relative to the total area of continental crust extracted from the empirical data of Smith et al. (1994) and Golonka et al. (2006) produced palaeoshoreline maps that matched the sea-level curves of Haq & Al-Qahtani (2005) and Müller (2008). Yet, the Smith et al. (1994)

and Golonka et al. (2006) models have a sparse data coverage across Southeast Asia, with no data points for New Guinea or Indonesia (apart from Kalimantan). Therefore, subtle regional deep marine incursions and the development of widespread carbonate platforms are not recorded in palaeogeographic reconstructions. Leprieur et al. (2016) take a different approach to mapping the development of carbonate platforms in Southeast Asia by using a mechanistic model of species diversification combined with a model of synthetic paleobathymetry estimates to map the global spatial distribution of biodiversity hotspots since the Cretaceous. This approach models the migration of new species and biodiversity hotspots through time, moving eastward from western Tethys through the Arabian Peninsula and Indian Ocean, eventually arriving in the Indo-Pacific during the Miocene (15-5 Ma) (Leprieur et al., 2016). Leprieur et al. (2016) remark that ecological diversification is controlled by the availability of tropical reef habitat through time. However, our models show that carbonate platforms flourished during the Middle-Late Eocene in western New Guinea (Fig. 9e). We therefore suggest that tropical reef habitats were available since at least the Eocene, much earlier than Leprieur et al., (2016) proposed. We speculate that the widespread carbonate platform development in western New Guinea during the Eocene may be controlled by regional tectonism and/or favourable environmental conditions that permitted high rates of carbonate production.

Although our palaeogeographic reconstructions do record changes in the long-term eustatic sea-level signal for the Paleozoic and Mesozoic, these deviate from published curves from the Paleogene and Neogene (Fig. 17). Where the long-term eustatic trend records a fall in sea-level from the Late Cretaceous to Oligocene; our



relative sea-level curve suggests a minor regional transgression between the Eocene and Oligocene (Fig. 17). Zahirovic et al. (2016) and Yang et al. (2016) suggested widespread flooding of the Sundaland platform occurred during the Eocene. Yet, this rise in relative sea-level occurred at a time of global eustatic sea level fall (Haq and Al-Qahtani, 2005; Müller, 2008; Snedden and Liu, 2010; Heine et al., 2015). Yang et al. (2016) proposed the mechanism for this was due dynamic topographic effects. Following continuing global sea-level fall in the Oligocene, many published curves indicate a rise in sea-level from the Early Miocene (Fig. 17). This contrasts to our curve which records localised sea-level fall, interpreted here to be caused by arc-continent collision between New Guinea and intra-Pacific island arcs between the Oligocene and Early Miocene resulting in localised uplift and halting the regional transgression of the Oligocene. Our regional relative sea-level curve for western New Guinea again records the global eustatic signal of sea-level rise throughout the Middle and Late Miocene, followed by sea-level fall to present day levels (Fig. 17). These examples reinforce the point that global sea-level curves are not typically appropriate for regions such as Southeast Asia, where complex tectonism and favourable environmental conditions for carbonate production are likely have a greater control on the palaeogeography than eustatic factors. Computer modelled palaeobathymetries (e.g. Müller et al., 2008) are often too coarse to be used as parameters to model subtle changes in palaeogeography at a regional scale. These models have the capability of computing global bathymetric changes in hundreds to thousands of metres water depth, however the use of palaeontological and sedimentological data, as shown by this study, can model changes in bathymetry at a scale from a few tens to hundreds of metres. Therefore, we propose that bathymetric models generated from local observational data sources allow for

much more robust reconstructions of regional palaeogeographies for plate margins than models that primarily rely on global eustasy curves. The challenge lies in developing representative relative sea-level curves from the available data sources and to use these to test and further develop more regional to global models.

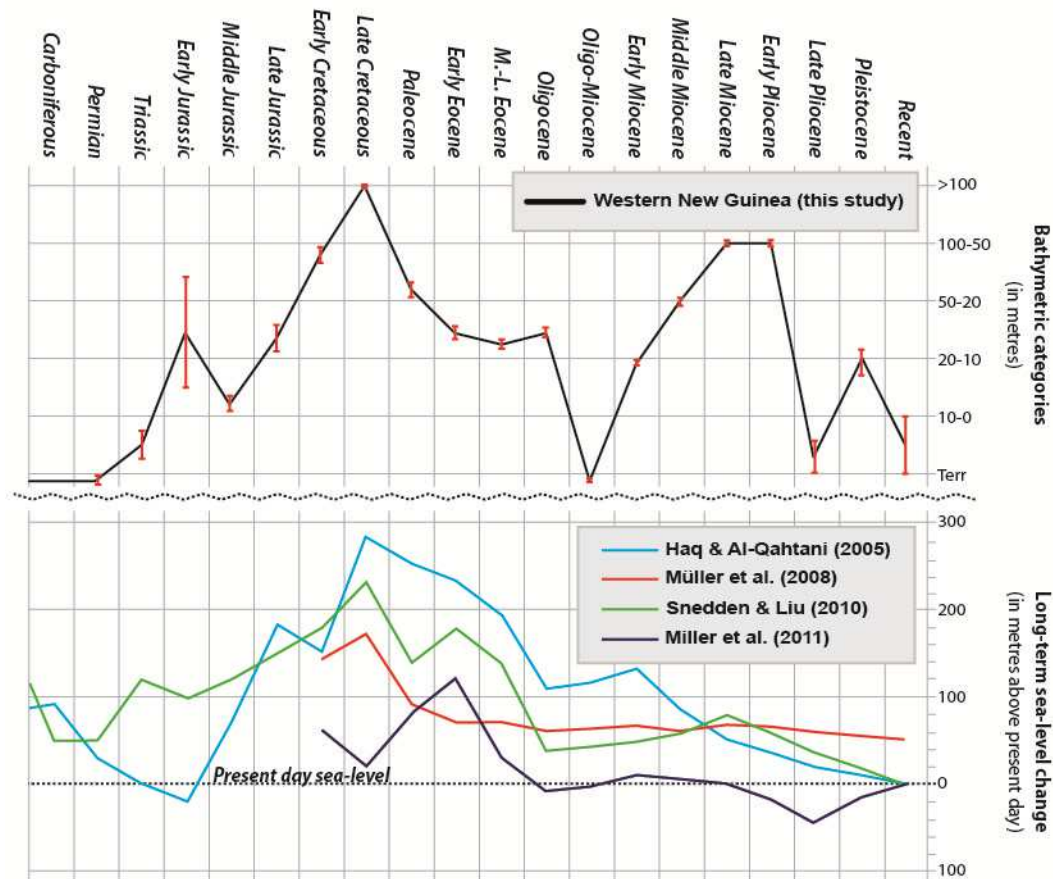


Figure 17

#### 5.4 Unconformities

Eight major unconformities are recognised across western New Guinea according to new biostratigraphic data as well as analyses of well logs and existing literature. Six of these unconformities are interpreted as sub-aerial unconformities as they are supported by evidence for terrestrial deposition in our palaeogeographic reconstructions (Figs. 7, 9, 13, 16). Where many wells do not contain evidence for terrestrial deposition, they instead exhibit a stratigraphic break that records a period

of non-deposition and/or erosion. The areas of non-deposition and/or erosion identified within the reviewed well data are depicted in Figure 18. The oldest sub-aerial unconformities occur above the Kemum Formation at the Devonian and Carboniferous boundary as well as during the Late Permian. These unconformities reflect predominantly terrestrial deposition of the Aifam Group during the Carboniferous. Similarly the Triassic and Early Jurassic unconformities are related to widespread terrestrial deposition of the Tipuma Formation. Where terrestrial sediments do not accumulate, are not preserved, or have been eroded, parts, or all, of the Carboniferous and Triassic-Jurassic successions are missing.

Further sub-aerial unconformities are interpreted to occur at the Oligocene-Miocene boundary, observed above the Sirga Formation, and during the Pliocene (Fig. 18). The Oligo-Miocene sub-aerial unconformity is interpreted to be related to uplift caused by arc-continent collision (e.g. Davies et al., 1996; Hall, 2002; Wilson, 2002; Hill and Hall, 2003; Gold et al., 2014). The intra-Pliocene unconformity (e.g. Pairault et al. 2003; Decker et al., 2009) is confined to the west of the Bird's Head. The age of emergence is recorded by biostratigraphic data to have occurred between 4.0 Ma and 3.4 Ma (Decker et al., 2009).

In addition to these unconformities, two other unconformities are recorded in the regional stratigraphy during the Late Cretaceous and Late Miocene. These coincide with peak transgressions shown in our palaeogeographic reconstructions. We interpret these hiatuses to represent drowning unconformities on the opposite end of the relative sea-level cycle to sub-aerial unconformities (e.g. Schlager, 1981; 1989; 1999). These types of unconformity are prone to forming condensed sections

(Schlager, 1989) where basinal areas are starved of sediment, thus producing a stratigraphic break in well successions. Little is known about the Late Cretaceous event, but recent work has shown that the Late Miocene drowning unconformity is related to the Middle to Late Miocene drowning of the widespread New Guinea Limestone Group carbonate platform (Gold et al., 2014).

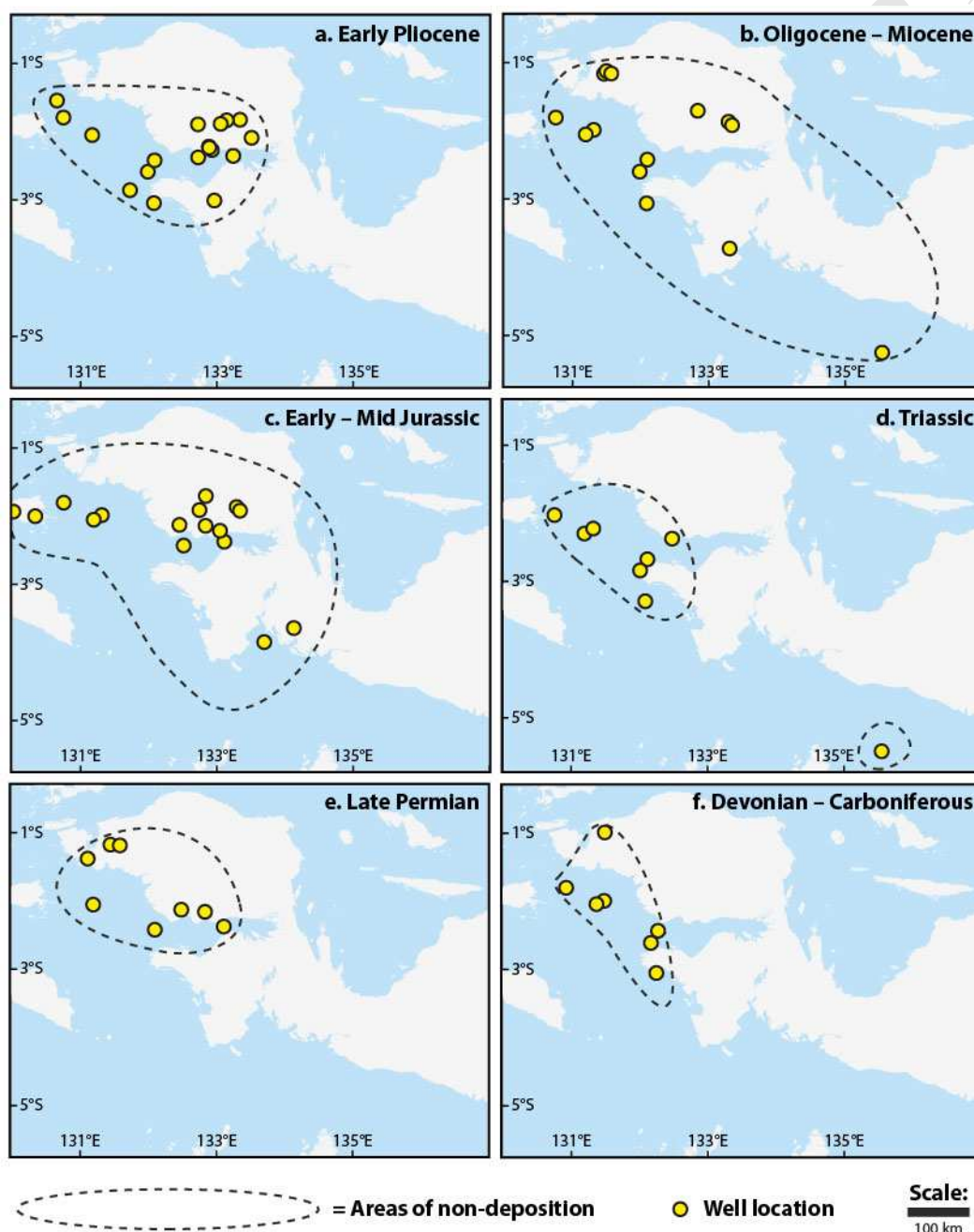


Figure 18

## 6. Conclusions

Empirical data from well and outcrop samples from Carboniferous to Recent sediments were used to reinterpret the paleogeographic evolution of western New Guinea and to examine the long-term regional record of sea-level change. We also showed that the use of empirical data to generate such maps, should lead to more robust documentation of regional changes in relative sea-level than semi-automated modelling methods that primarily rely on global eustatic sea-level curves. In western New Guinea, relative sea-levels were highest during the Late Cretaceous and Late Miocene. These peaks correspond with those identified in long-term eustatic sea-level change. However, from the Eocene to Oligocene the relative sea-level curve deviates from the long-term global eustatic sea-level. We attribute this change to regional tectonism and/or environmental factors, such as higher atmospheric and sea-water temperatures that may have facilitated greater carbonate production. If we consider that the latitude and position of New Guinea relative to Australia has not changed considerably since the Triassic then our palaeogeographic reconstructions south of the Australia-Pacific suture from the Triassic onwards are relatively robust. The palaeoenvironmental interpretations of the post-collisional stratigraphy of the region are also quite robust, however, these do not account for any deformation associated with the interaction between the Pacific and Australian plates, which is something that we will address in future.

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## References

- Adams, C.G., 1965. The foraminifera and stratigraphy of the Melinau Limestone, Sarawak, and its importance in Tertiary correlation. *Quarterly Journal of the Geological Society* 121(1-4), 283-338.
- Adams, C.G., 1970. A reconsideration of the East Indian letter classification of the Tertiary, *Bulletin of the British Museum (Natural History). Geology* 19, 87-137.
- Ajam, S.O., Henzell, L.A., Wang, J., Syarif, A. M. and Soedirdja, H., 1982. Wellsite log evaluation of the Miocene carbonates in Salawati basin. *Proceedings of the 11<sup>th</sup> Indonesian Petroleum Association Annual Convention and Exhibition*, 357-378.
- Ali, J. R. and Hall, R. 1995. Evolution of the boundary between the Philippine Sea Plate and Australia: Palaeomagnetic evidence from eastern Indonesia. *Tectonophysics* 251 (1-4), 251-275.
- Atmawinata, S., Ratman, N. and Pieters, P. E., 1989. *Geologi Lembar Yapen, Irian Jaya (Geology of the Yapen Sheet area, Irian Jaya)*. Geological Research and Development Centre, Indonesia.

- Audley-Charles, M.G., 1965. Permian palaeogeography of the northern Australia-Timor region. *Palaeogeography, Palaeoclimatology, Palaeoecology* 1, 297-305.
- Audley-Charles, M., 1966. Mesozoic palaeogeography of Australasia. *Palaeogeography, Palaeoclimatology, Palaeoecology* 2, 1-25.
- Baillard, F., Gold, D. P., Rathore, R., Zhang, Z., Arbi, S. and Hardenberg, M. 2017. Prospect de-risking through a fully integrated approach from seismic processing to geology interpretation. Proceedings Indonesian Petroleum Association 41st Annual Convention & Exhibition, IPA17-29-G, 16pp.
- Bailly, V., Pubellier, M., Ringenbach, J-C., de Sigoyer, J., and Sapin, F., 2009. Deformation zone 'jumps' in a young convergent setting; the Lengguru fold-and-thrust belt, New Guinea Island. *Lithos* 113, 306-317.
- Baldwin, S.L. and Ireland, T.R., 1995. A tale of two eras: Pliocene-Pleistocene unroofing of Cenozoic and late Archean zircons from active metamorphic core complexes, Solomon Sea, Papua New Guinea. *Geology* 23(11), 1023-1026.
- Baldwin, S.L., Monteleone, B.D., Webb, L.E., Fitzgerald, P.G., Grove, M. and Hill, E.J., 2004. Pliocene eclogite exhumation at plate tectonic rates in eastern Papua New Guinea. *Nature* 431(7006), 263-267.

- Baldwin, S. L., Fitzgerald, P. G. and Webb, L. E. 2012. Tectonics of the New Guinea Region. *Annual Reviews from Earth and Planetary Science* 40, 495-520.
- Bé, A. W. H., 1977. An ecological, zoogeographic and taxonomic review of Recent planktonic foraminifera. In: Ramsey, A.T.S. (Ed), *Oceanic micropalaeontology*. Academic Press, London, 1-100.
- Beavington-Penney, S.J. and Racey, A., 2004. Ecology of extant nummulitids and other larger benthic foraminifera: applications in palaeoenvironmental analysis. *Earth-Science Reviews* 67(3), 219-265.
- Belford, D. J., 1991. A record of the genus *Lockhartia* (foraminiferida) from Missol archipelago, Irian Jaya. *BMR Journal of Australian geology*, 297-299
- Berggren, W.A. and Miller, K.G., 1988. Paleogene tropical planktonic foraminiferal biostratigraphy and magnetobiochronology. *Micropaleontology*, 362-380.
- Berggren W.A., Kent, D.V., Swisher, C.C., III, Aubry, M.-P., 1995. A revised Cenozoic geochronology and chronostratigraphy. In: Berggren, W.A., Kent, D.V., Aubry, M.-P., Hardenbol, J. (Eds.), *Geochronology, Time Scales, and Stratigraphic Correlation: Framework for an Historical Geology*. SEPM Special Publication 54, 129-212.

- Bladon, G. M., 1988. Preliminary geological report. Catalogue, appraisal and significance of K-Ar isotopic ages determined for igneous and metamorphic rocks in Irian Jaya, Indonesia-Australia Geological Mapping Project, 79pp.
- Blow, W.H., 1979. The cainozoic Globigerinida: a study of the morphology, taxonomy, evolutionary relationships and the stratigraphical distribution of some Globigerinida (mainly Globigerinacea). Text: P. 1/2: Sect. 1. Brill.
- BouDagher-Fadel, M. K., 2008. Evolution and geological significance of larger benthic foraminifera. Developments in palaeontology and stratigraphy 21. Elsevier, Amsterdam.
- BouDagher- Fadel, M.K., 2015. Biostratigraphic and geological significance of planktonic foraminifera. UCL Press, London.
- Brash, R. A., Henage, L. F., Harahap, B. H., Moffat, D. T., & Tauer, R. W., 1991. Stratigraphy and depositional history of the New Guinea limestone group, Lengguru, Irian Jaya. Proceedings Indonesian Petroleum Association 12<sup>th</sup> Annual Convention, 67-84.
- Challinor, A. B., 1990. A belemnite biozonation for the Jurassic-Cretaceous of Papua New Guinea and a faunal comparison with eastern Indonesia. BMR Journal of Australian Geology, 429-447.

- 1252 Charlton, T.R., 2001. The Permo-Triassic evolution of Gondwanan eastern  
1253 Indonesia, and the final Mesozoic separation of SE Asia from Australia. *Journal*  
1254 *of Asian Earth Sciences* 19, 595-617.  
1255
- 1256 Charlton, T. R., 2010. The Pliocene-recent anticlockwise rotation of the Bird's Head,  
1257 the opening of the Aru trough – Cenderawasih bay sphenochasm, and the  
1258 closure of the Banda double arc. *Proceedings of the 34<sup>th</sup> Indonesian Petroleum*  
1259 *Association convention and exhibition*, IPA10-G-008.  
1260
- 1261 Chevallier, B. and Bordenave, M. L., 1986. Contribution of geochemistry to the  
1262 exploration in the Bintuni Basin, Irian Jaya. *Proceedings Indonesian Petroleum*  
1263 *Association 15<sup>th</sup> Annual Convention* 1, 439-460.  
1264
- 1265 Cloos, M., Sapiie, B., van Ufford, A. Q., Weiland, R. J., Warren, P. Q. & McMahon, T.  
1266 P., 2005. Collisional delamination in New Guinea: The geotectonics of  
1267 subducting slab breakoff. *Geological Society of America Special Paper* 400, 1-  
1268 46.  
1269
- 1270 Collins, J.L. and Qureshi, M.K., 1977. Reef Exploration in Bintuni Basin and  
1271 Bomberai Trough–Irian Jaya. *Proceedings Indonesian Petroleum Association*  
1272
- 1273 Crowhurst, P.V., Maas, R., Hill, K.C., Foster, D.A. and Fanning, C.M., 2004. Isotopic  
1274 constraints on crustal architecture and Permo-Triassic tectonics in New Guinea:  
1275 possible links with eastern Australia. *Australian Journal of Earth Sciences*  
1276 51(1), 107-124.



1277

1278 Darman, H. and Sidi, F.H., 2000. An Outline of the Geology of Indonesia. Indonesia  
1279 Association of Geologists, 1-192.

1280

1281 Davies, H.L. and Jaques, A.L., 1984. Emplacement of ophiolite on Papua New  
1282 Guinea. In: Gass, I.G., Lippard, S.J. and Shelton, A.W. (Eds.), Ophiolites and  
1283 Oceanic Lithosphere. Geological Society of London Special Publication 14,  
1284 341–349.

1285

1286 Davies, H. L., Winn, R. D. and KenGemar, P., 1996. Evolution of the Papuan Basin –  
1287 a view from the orogeny. In: Buchanan, P. G. (Ed), Petroleum Exploration,  
1288 Development and Production in Papua New Guinea. Proceedings of the Third  
1289 PNG Petroleum Convention, 53-62

1290

1291 Davies, H.L., 2012. The geology of New Guinea-the cordilleran margin of the  
1292 Australian continent. Episodes 35(1), 87-102.

1293

1294 Dawson, O., 1993. Fusiline foraminiferal biostratigraphy and carbonate facies of the  
1295 Permian Ratburi Limestone, Saraburi, central Thailand. Journal of  
1296 Micropalaeontology 12, 9-33.

1297

1298 Decker, J., Bergman, S. C., Teas, P. A., Baillie, P. and Orange, D. L., 2009.  
1299 Constraints on the tectonic evolution of the Bird's Head, West Papua,  
1300 Indonesia. Proceedings Indonesian Petroleum Association 33rd Annual  
1301 Convention & Exhibition, 491-514. IPA-G-139.

- Decker, J., Ferdian, F., Morton, A., Fanning, M., White, L. T., 2017. New geochronology data from eastern Indonesia – an aid to understanding sedimentary provenance in a frontier region. Proceedings Indonesian Petroleum Association 41st Annual Convention & Exhibition, IPA17-551-G, 18pp.
- Dolan, P.J. and Hermany, 1988. The geology of the Wiriagar Field, Bintuni Basin, Irian Jaya. Proceedings of the 17<sup>th</sup> Indonesian Petroleum Association Annual Convention and Exhibition, 53-87. IPA88-11-14.
- Dow, D.B., Harahap, B.H. and Hakim, S.A., 1990. Geology of the Enarotali Sheet area, Irian Jaya, Geological Survey of Indonesia, Directorate of Mineral Resources, Geological Research and Development Centre, Bandung.
- Dow, D.B., Robinson, G.B., Hartono, U. and Ratman, N., 1986. Geologic map of Irian Jaya, Indonesia, 1:1,000,000 scale. Geological Research and Development Centre, Indonesia
- Fontaine, H., 2001. Permian of Southeast Asia – a review. Journal of Asian Earth Sciences 20, 567-588.
- François, C., de Sigoyer, J., Pubellier, M., Bailly, V., Cocherie, A. and Ringenbach, J.C., 2016. Short-lived subduction and exhumation in Western Papua

(Wandamen peninsula): Co-existence of HP and HT metamorphic rocks in a young geodynamic setting. *Lithos* 266, 44-63.

Fraser T.H., Bon J., Samuel L., Rukmiati M.G. and Imam Hardjo J., 1993, A new dynamic Mesozoic stratigraphy for the west Irian micro-continent, Indonesia, and its implications: Proceedings of the Indonesian Petroleum Association, 22nd Annual Convention, 707–761.

Gibson-Robinson, C. and Soedirdja, H., 1986. Transgressive development of Miocene reefs, Salawati Basin, Irian Jaya. Proceedings Indonesian Petroleum Association 15<sup>th</sup> Annual Convention, 377-403.

Gold, D., Hall, R., Burgess, P. and BouDagher-Fadel, M., 2014. The Biak Basin and its Setting in the Bird's Head Region of West Papua. Proceedings of the 38<sup>th</sup> Indonesia Petroleum Association Annual Convention and Exhibition.

Golonka, J., Krobicki, M., Pajak, J., Van Giang, N. and Zuchiewicz, W., 2006, Global Plate Tectonics and Paleogeography of Southeast Asia, 1-128. Fac. of Geol., Geophys. and Environ. Prot., AGH Univ. of Sci. and Technol., Krakow, Poland.

Golonka, J., 2009. Phanerozoic paleoenvironment and paleolithofacies maps: Cenozoic. *Geologia/Akademia Górniczo-Hutnicza im. Stanisława Staszica w Krakowie* 35, 507-587.

- 1350 Gradstein, F.M., Ogg, J.G., Schmitz, M. and Ogg, G., 2012. The geologic time scale  
1351 2012. Elsevier.
- 1352
- 1353 Gunawan, I., Hall, R. and Sevastjanova, I., 2012. Age, character and provenance of  
1354 the Tipuma Formation, West Papua: New insights from detrital zircon dating.  
1355 Proceedings Indonesian Petroleum Association 36th Annual Convention,  
1356 IPA12-G-027, 1-14.
- 1357
- 1358 Gunawan, I., Hall, R., Augustsson, C. and Armstrong, R., 2014. Quartz from the  
1359 Tipuma Formation, West Papua: new insights from geochronology and  
1360 cathodoluminescence studies. Proceedings of the Indonesian Petroleum  
1361 Association 38<sup>th</sup> Annual Convention and Exhibition, IPA14-G-303
- 1362
- 1363 Hall, R., 2002. Cenozoic geological and plate tectonic evolution of SE Asia and the  
1364 SW Pacific: computer-based reconstructions, model and animations. Journal of  
1365 Asian Earth Sciences 20, 353-431.
- 1366
- 1367 Hall, R., 2012. Late Jurassic–Cenozoic reconstructions of the Indonesian region and  
1368 the Indian Ocean. Tectonophysics 570-571, 1-41.
- 1369
- 1370 Hallock, P. and Glenn, E.C., 1986. Larger foraminifera: a tool for paleoenvironmental  
1371 analysis of Cenozoic carbonate depositional facies. *Palaios*, 55-64.
- 1372
- 1373 Haq, B.U., Hardenbol, J. and Vail, P.R., 1987. The new chronostratigraphic basis of  
1374 Cenozoic and Mesozoic sea level cycles. Timing and depositional history of

eustatic sequences: constraints on seismic stratigraphy. Cushman Foundation  
for Foraminiferal Research Special Publications 24, 7-13.

Haq, B.U. and Al-Qahtani, A.M., 2005. Phanerozoic cycles of sea-level change on  
the Arabian Platform. *GeoArabia* 10(2), 127-160.

Haq, B.U. and S.R. Shutter, 2008, A chronology of Paleozoic sea-level changes.  
*Science* 322, 64-68.

Haq, B.U., 2014. Cretaceous eustasy revisited. *Global and Planetary Change* 113,  
44-58.

Harahap, B.H., Hakim, A.S. and Dow, D.B., 1990. Peta geologi lembar Enarotali,  
Irian Jaya (Geological Map of the Enarotali Quadrangle, Irian Jaya). Geological  
Research and Development Centre, Indonesia

Hardenbol, J., J. Thierry, M.B. Farley, T. Jacquin, P.C. de Graciansky, and P. Vail,  
1998. Mesozoic and Cenozoic sequence chronostratigraphic framework of  
European basins. In: Graciansky, P.C. et al. (Eds.) *Mesozoic and Cenozoic  
Sequence Stratigraphy of European Basins*. SEPM Special Publication 60, 3-  
13, charts 1-8.

Hasibuan, F., 1990. Mesozoic Stratigraphy and Paleontology of Misoot Archipelago,  
Indonesia. PhD Thesis University of Auckland



- 1400 Heine, C., Yeo, L.G. and Müller, R.D., 2015. Evaluating global paleoshoreline  
1401 models for the Cretaceous and Cenozoic. *Australian Journal of Earth Sciences*,  
1402 62(3), 275-287.
- 1403
- 1404 Hendarjo, K. S. and Netherwood, R. E. 1986. Palaeoenvironmental and diagenetic  
1405 history of Kais Formation, KBSA, Irian Jaya. *Proceedings Indonesian*  
1406 *Petroleum Association 15<sup>th</sup> Annual Convention*, 423-438.
- 1407
- 1408 Hill, K. C. and Hall, R., 2003. Mesozoic-Cainozoic evolution of Australia's New  
1409 Guinea Margin in a west Pacific context. In: Hillis, R. and Müller, R. D. (Eds)  
1410 *Defining Australia: The Australian Plate as part of Planet Earth*. Geological  
1411 *Society of America Special Paper/Geological Society of Australia Special*  
1412 *Publication 372*, 265-290.
- 1413
- 1414 Hill, K. C., 1991. Structure of the Papuan fold belt, Papua New Guinea. *American*  
1415 *Association of Petroleum Geologists Bulletin* 75, 857–872
- 1416
- 1417 Holm, R.J. and Richards, S.W., 2013. A re-evaluation of arc–continent collision and  
1418 along-arc variation in the Bismarck Sea region, Papua New Guinea. *Australian*  
1419 *Journal of Earth Sciences*, 60(5), 605-619.
- 1420
- 1421 Holm, R.J., Spandler, C. and Richards, S.W., 2015. Continental collision, orogenesis  
1422 and arc magmatism of the Miocene Maramuni arc, Papua New Guinea.  
1423 *Gondwana Research* 28(3), 1117-1136.
- 1424

- 1425 Holm, R.J., Rosenbaum, G. and Richards, S.W., 2016. Post 8 Ma reconstruction of  
1426 Papua New Guinea and Solomon Islands: Microplate tectonics in a convergent  
1427 plate boundary setting. *Earth-Science Reviews* 156, 66-81.
- 1428
- 1429 Kato, M., Sundari, D. and Skwarko, S.K., 1999. First description of Carboniferous  
1430 corals from Western Irian Jaya, Indonesia. *Seri Paleontologi* 9, 9-41.
- 1431
- 1432 Kendrick, R.D. and Hill, K.C., 2002. Hydrocarbon play concepts for the Irian Jaya  
1433 fold belt. *Proceedings of the 28<sup>th</sup> Indonesian Petroleum Association Annual  
1434 Convention and Exhibition*, 353-367. IPA01-G-087.
- 1435
- 1436 Koesoemadinata, R.P., 1976. Tertiary carbonate sedimentation in Irian Jaya with  
1437 special reference to the northern part of the Bintuni Basin. *Proceedings of the  
1438 Indonesia Petroleum Association Carbonate Seminar*, 79-92.
- 1439
- 1440 Leprieur, F., Descombes, P., Gaboriau, T., Cowman, P.F., Parravicini, V., Kulbicki,  
1441 M., Melián, C.J., De Santana, C.N., Heine, C., Mouillot, D. and Bellwood, D.R.,  
1442 2016. Plate tectonics drive tropical reef biodiversity dynamics. *Nature  
1443 communications* 7.
- 1444
- 1445 Livingstone, H.J., Sincock, B.W., Syarief, A.M., Sriwidadi and Wilson, J.N., 1992.  
1446 Comparison of Walio and Kasim reefs, Salawati Basin, western Irian Jaya,  
1447 Indonesia. *Proceedings of the Indonesian Petroleum Association Carbonate  
1448 rocks and reservoirs of Indonesia – a core workshop*
- 1449

- Lunt, P., 2013. Foraminiferal micropalaeontology in SE Asia. In: Bowden, A.J. et al. (Eds.) Landmarks in foraminiferal micropalaeontology: history and development, The Micropalaeontological Society Special Publication 6, Geological Society of London, 193-206.
- Lunt, P., and Djaafar, R., 1991, Aspects of the stratigraphy of western Irian Jaya and implications for the development of sandy facies. Proceedings Indonesian Petroleum Association 20th Annual Convention, 107–124. IPA91-11.10.
- Martini, R., Zaninetti, L., Lathuilliere, B., Cirilli, S., Cornée, J.J. and Villeneuve, M., 2004. Upper Triassic carbonate deposits of Seram (Indonesia): palaeogeographic and geodynamic implications. *Palaeogeography, Palaeoclimatology, Palaeoecology* 206(1), 75-102.
- Martodjojo, S., Sudradjat, D., Subandrio, E. and Lukman, A., 1975. The geology and stratigraphy along the road cut Tembagapura, Irian Jaya [Indonesia] 1, 1-51 (unpublished report).
- Masria, M., Ratman, N. and Suwitodirdjo., 1981. Geologi lembar Biak, Irian Jaya (The geology of the Biak Quadrangle, Irian Jaya), Geological Research and Development Centre, Indonesia, 1-10.
- Metcalf, I., 1998. Palaeozoic and Mesozoic geological evolution of the SE Asian region: multidisciplinary constraints and implications for biogeography. *Biogeography and geological evolution of SE Asia*, 25-41.

- 1476
- 1477 Metcalfe, I., 2009, Late Palaeozoic and Mesozoic tectonic and palaeogeographical  
1478 evolution of SE Asia. In Buffetaut, E., Cuny, G., Loeuff, J.L., and Suteethorn,  
1479 V., (Eds.), Late Palaeozoic and Mesozoic ecosystems in SE Asia. Geological  
1480 Society of London Special Publication 315, 7–23.
- 1481
- 1482 Miller, K.G., G.S. Mountain, J.D. Wright, and J.V. Browning., 2011. A 180-million-  
1483 year record of sea level and ice volume variations from continental margin and  
1484 deep-sea isotopic records. *Oceanography* 24(2), 40–53.
- 1485
- 1486 Milsom, J., Masson, D., Nichols, G., Sikumbang, N., Dwiyanto, B., Parson, L. and  
1487 Kallagher, H., 1992. The Manokwari Trough and the western end of the New  
1488 Guinea Trench. *Tectonics* 11 (1), 145-153.
- 1489
- 1490 Müller, R.D., Sdrolias, M., Gaina, C., Steinberger, B. and Heine, C. 2008. Long-term  
1491 sea-level fluctuations driven by ocean basin dynamics. *Science* 319, 1357–  
1492 1362.
- 1493
- 1494 Murray, J.W., 2006. Ecology and applications of benthic foraminifera. Cambridge  
1495 University Press.
- 1496
- 1497 Musper, K. A. F. R., 1938. Over het voorkomen van *Halysites wallichi* Reed op  
1498 Nieuw-Guinea. *De Ingenieur in Nederlandsch-Indid'*, IV, Mijnbouw en Geologie  
1499 10, 156-158.
- 1500

- 1501 Nicoll, R. S. and Bladon, G. M., 1991. Silurian and Late Carboniferous conodonts  
1502 from the Charles Louis Range and central Birds Head, Irian Jaya, Indonesia. B.  
1503 M. R. Journal of Australian Geology and Geophysics 12, 279-286.  
1504
- 1505 Norvick, M.S., 2003. New palaeogeographic maps of the northern margins of the  
1506 Australian plate: updated report. Unpublished report for Geoscience Australia,  
1507 September 2003.  
1508
- 1509 O'Sullivan, P. B., Hill, K.C., Saefudin, I. and Kendrick, R.D., 1995. Mesozoic and  
1510 Cenozoic thermal history of sedimentary rocks in the Bintuni Basin, Irian Jaya,  
1511 Indonesia. Proceedings of the Indonesian Petroleum Association 24<sup>th</sup> Annual  
1512 Convention and Exhibition, 235-248. IPA95-1.1-156.  
1513
- 1514 Oliver Jr, W.A., Pedder, A.E.H., Weiland, R.J. and van Ufford, A.Q., 1995. Middle  
1515 Palaeozoic corals from the southern slope of the Central Ranges of Irian Jaya,  
1516 Indonesia. Alcheringa 19(1), 1-15.  
1517
- 1518 Pairault, A.A., Hall, R. and Elders, C.F., 2003. Structural Styles and Tectonic  
1519 Evolution of the Seram Trough, Indonesia. Marine and Petroleum Geology 20,  
1520 1141–1160.  
1521
- 1522 Panggabean, H., Amiruddin, Kusnama, Sutisna, K., Situmorang, R.L., Turkandi, T.  
1523 and Hermanto, B., 1995. Peta geologi lembar Beoga, Irian Jaya (Geological  
1524 Map of the Beoga Quadrangle, Irian Jaya). Geological Research and  
1525 Development Centre, Indonesia



- Parris K. R., 1994. Preliminary Geological Data Record of the Timika (3211) 1:250  
000 Sheet Area, Irian Jaya. PT Freeport Indonesia Report (unpubl.).
- Pieters, P. E., Pigram, C. J., Trail, D. S., Dow, D. B, Ratman, N. and Sukanto, R.,  
1983. The stratigraphy of the western Irian Jaya. Bulletin of the Geological  
Research and Development Centre 8, 14-48.
- Pieters, P. E., Hakim, A. S. and Atmawinata, S., 1990. Geologi lembar Ransiki, Irian  
Jaya (Geology of the Ransiki sheet area, Irian Jaya), Geological Research and  
Development Centre, Indonesia
- Pieters, P. E., Hartono, U. and Amri, C., 1989. Geologi lembar Mar, Irian Jaya  
(Geology of the Mar sheet area, Irian Jaya), Geological Research and  
Development Centre, Indonesia
- Pigram, C.J., Robinson, G.P. and Tobing, S.L., 1982. Late Cainozoic origin for the  
Binutni Basin and adjacent Lengguru fold belt, Irian Jaya. Proceedings of the  
11th Indonesian Petroleum Association Annual Convention and Exhibition, 109-  
126.
- Pigram, C. J. and Davies, H. L., 1987. Terranes and accretion history the New  
Guinea orogeny. Bureau of Mineral Resources Journal of Australian Geology  
and Geophysics 10, 193-212.

- Pigram, C. J. and Symonds, P. A. 1991. A review of the timing of the major tectonic events in the New Guinea orogen. *Journal of Southeast Asian Earth Sciences* 6, 307-318.
- Redman, J. L. and Koesoemadinata, R. P., 1976. Walio oil field and the Miocene carbonates of Salawati basin, Irian, Jaya, Indonesia. *Proceedings, Indonesian Petroleum Association Fifth Annual Convention and Exhibition*, 41-57.
- Repsol Investor Relations, 2014. Exploration Day 2014 presentation, London January 29th 2014. Accessed at: [https://imagenes.repsol.com/es\\_en/Exploration\\_Day\\_2014\\_CNMV\\_29\\_01\\_2014\\_tcm11-670726.pdf](https://imagenes.repsol.com/es_en/Exploration_Day_2014_CNMV_29_01_2014_tcm11-670726.pdf)
- Robinson, G. P., Ratman, N. and Pieters, P. E., 1990. Geology of the Manokwari sheet area, Irian Jaya, Geological Survey of Indonesia, Directorate of Mineral Resources, Geological Research and Development Centre, Bandung
- Ross, C.A. and Ross, J.R.P., 1988. Late Paleozoic transgressive-regressive deposition. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G., Posamentier, H.W., Ross, C.A. & Van Wagoner, J.C. (Eds.), *Sea-Level Changes - An Integrated Approach*. SEPM Special Publication 42, 227-247.
- Schlager, W., 1981. The paradox of drowned reefs and carbonate platforms. *Geological Society of America Bulletin* 92(4), 197-211.

- 1576 Schlager, W., 1989. Drowning unconformities on carbonate platforms. In: Crevello,  
1577 P. D., Wilson, J. L., Sarg, J. F., Read, J. F. (Eds.), Controls of carbonate  
1578 platform and basin development. SEPM Special Publication 44, 15-27.  
1579
- 1580 Schlager, W., 1999. Type 3 sequence boundaries. In: Harris, P.M., Saller, A.H. and  
1581 Simo, J.A. (Eds.), Advances in carbonate sequence stratigraphy application to  
1582 reservoirs outcrops and models. SEPM Special Publication 63, 35-45.  
1583
- 1584 Smith A., Smith D. G. and Furnell B. M., 1994. Atlas of Mesozoic and Cenozoic  
1585 coastlines, Cambridge University Press, Cambridge, United Kingdom, 1-112.  
1586
- 1587 Snedden, J.W. & Liu, C., 2010. A compilation of Phanerozoic sea-level change,  
1588 coastal onlaps and recommended sequence designations. AAPG Search and  
1589 Discovery Article 40594.  
1590
- 1591 Teichert, C., 1928. Nachweis Paläozoischer Schichten von Siidwest-Neu-Guinea. In  
1592 De Beaufort, L.F., Pulle, A.A. and Rutten, L. (Eds.), Nova Guinea: Resultats  
1593 des Expeditione Scientifiques a la Nouvelle Guinee, 6, Geologie 3, 71-92.  
1594
- 1595 Valenta, W.T., 1979. Seismic modelling of porosity distribution in a Miocene reef,  
1596 Salawati Island, Indonesia. Proceedings of the 8<sup>th</sup> Indonesian Petroleum  
1597 Association Annual Convention and Exhibition, 159-176.  
1598
- 1599 Van Bemmelen, R. W., 1949. The Geology of Indonesia. Government Printing Office,  
1600 The Hague, 1-732.

- Van Gorsel, J.T., 1988. Biostratigraphy in Indonesia: methods, pitfalls and new directions. . Proceedings, Indonesian Petroleum Association Annual Convention
- Van Gorsel, J. T., 2012. Middle Jurassic Ammonites from the Cendrawasih Bay Coast and North Lengguru Fold-Belt, West Papua: Implications of a ‘forgotten’ 1913 Paper, *Berita Sedimentologi* 23, 35-41.
- Vincelette, R. R., 1973. Reef exploration in Irian Jaya, Indonesia. Proceedings of the second Indonesian Petroleum Association annual convention and exhibition
- Visser, W.A. & Hermes, J.J., 1962. Koninklijk Nederlands Geologisch Mijnbouwkundig genootschap Verhandelingen Geologische (Geological results of the search for oil in Netherlands New Guinea). *Nederlandsche Nieuw Guinee Petroleum Maatschappij*.
- Waschmuth, W. and F. Kunst, 1986. Wrench Fault Tectonics in Northern Irian Jaya. Proceedings Indonesian Petroleum Association 15<sup>th</sup> Convention, 371-375.
- Wade, B. S., Pearson, P. N., Berggren, W. A., & Pälike, H., 2011. Review and revision of Cenozoic tropical planktonic foraminiferal biostratigraphy and calibration to the geomagnetic polarity and astronomical time scale. *Earth-Science Reviews* 104, 111–142.

- Webb, M., White, L.T., 2016. Age and nature of Triassic magmatism in the Netoni Intrusive Complex, West Papua, Indonesia, *Journal of Asian Earth Sciences*
- Westermann, G.E.G. and Callomon, J.H., 1988. The Macrocephalitinae and associated Bathonian and early Callovian (Jurassic) ammonoids of the Sula islands and New Guinea. *Palaeontographica A* 203, 1-90.
- Westermann, G.E.G., 1992. *Jurassic of the Circum-Pacific*. Cambridge University Press.
- Westermann, G.E., 2000. Marine faunal realms of the Mesozoic: review and revision under the new guidelines for biogeographic classification and nomenclature. *Palaeogeography, Palaeoclimatology, Palaeoecology* 163(1), 49-68.
- White, L. T., Morse, M. P., Lister, G. S. 2014. Lithospheric-scale structures in New Guinea and their control on the location of gold and copper deposits. *Solid Earth* 5, 163–179.
- Wilson, M. E. J. 2002. Cenozoic carbonates in Southeast Asia: implications for equatorial carbonate development. *Sedimentary Geology* 147, 295– 428.
- Yang, T., Gurnis, M. and Zahirovic, S., 2016. Mantle-induced subsidence and compression in SE Asia since the early Miocene. *Geophysical Research Letters*, 43(5), 1901-1909.



Zahirovic, S., Flament, N., Dietmar Müller, R., Seton, M. and Gurnis, M., 2016. Large fluctuations of shallow seas in low-lying Southeast Asia driven by mantle flow. *Geochemistry, Geophysics, Geosystems* 17(9), 3589-3607.

Zahirovic, S., Seton, M. and Müller, R.D., 2014. The Cretaceous and Cenozoic tectonic evolution of Southeast Asia. *Solid Earth* 5(1), 1335-1422.

### Figure Captions

Figure 1. Map of (a) New Guinea and (b) western New Guinea which represents the focus of this study. These indicate the location of various geographic and geological names that are discussed in the text. A dashed line is also shown in (a). This broadly represents the boundary between basement rocks with an Australian affinity (to the south) and Pacific affinity (to the north).

Figure 2. A simplified lithological map of western New Guinea based on the distribution of lithologies shown on earlier GRDC maps and work conducted as part of this study. The map shows the location of recent sediments; fault and mud volcano melange; siliciclastics; carbonates; volcanics; intrusives; ultramafic and metamorphic rocks. Readers should note that the map does not provide any indication of the age of the rocks. The map was modified from Masria et al. (1981); Pieters et al. (1989); Robinson et al. (1990); Pieters et al. (1990); Brash et al. (1991).

Figure 3. Simplified stratigraphy of the Silurian to Jurassic rocks of western New Guinea, from Misool in the west (left hand side), through mainland West Papua (broadly from west to east) and Yapen island.

Figure 4. Simplified stratigraphy of the Cretaceous to Recent rocks of western New Guinea, from Misool in the west (left hand side), through mainland West Papua (broadly from west to east) to the islands of Biak, Supiori and Yapen.

Figure 5. The bathymetric boundaries used in the palaeogeographic reconstructions are derived from environmental preferences of foraminifera observed in this study. Thick lines indicate environments in which foraminifera are abundant, thin lines indicate environments in which they also occur infrequently. Environmental preferences are based on field data and Bé (1977), Hallock and Glenn (1986), van Gorsel (1988), Brash et al., 1991; BouDagher-Fadel (2008, 2015), Beavington-Penney and Racey (2004), Lunt (2013).

Figure 6. Location of hydrocarbon exploration wells were data were reinterpreted as part of this study. The numbers refer to the name of a particular well. Further details about each well and the references with information on these public domain wells are provided in Supp. Data 1.

Figure 7. Palaeogeographic reconstructions of western New Guinea, showing the paleogeographic evolution in the (a) Carboniferous; (b) Permian; (c) Triassic; (d) Early Jurassic; (e) Middle Jurassic, and the (f) Late Jurassic. These maps are based

on the synthesis of biostratigraphic data and interpreted paleodepositional environments from public domain well data, biostratigraphic reports, regional geology, sedimentological interpretations and new outcrop data. The number of data points used for each map are indicated in each time slice (e.g. n = 'x') and are shown as white dots. These data provide readers with some indication of our level of certainty for each reconstructions/region.

Figure 8. Bathonian-Callovian aged ammonites collected from the Kopai Formation close to the village of Wendesi. A) *Macrocephalites keeuwensis*, B) *Sphaeroceras boehmi* and C) *Holcophylloceras indicum*

Figure 9. Palaeogeographic reconstructions of western New Guinea, showing the paleogeographic evolution in the (a) Early Cretaceous; (b) Late Cretaceous; (c) Paleocene; (d) Early Eocene; (e) Middle-Late Eocene, and the (f) Oligocene. These maps are based on the synthesis of biostratigraphic data and interpreted paleodepositional environments from public domain well data, biostratigraphic reports, regional geology, sedimentological interpretations and new outcrop data. The number of data points used for each map are indicated in each time slice (e.g. n = 'x') and are shown as white dots. These data provide readers with some indication of our level of certainty for each reconstructions/region.

Figure 10. Age-diagnostic Late Cretaceous planktonic foraminifera, and key palaeoenvironmental indicators, observed in outcrop samples. (a–d) Carinate morphologies indicative of water depths greater than 100m. (e–f) Globular planktonic

1724 foraminifera. Key - *Globotruncana* spp.(G), *Contusotruncana fornicata* (C.f),  
 1725 *Globotruncana arca* (G.a), *Globotruncana bulloides* (G.b), *Heterohelix globulus*.  
 1726 (*H.g*).

1727

1728 Figure 11. Age-diagnostic Early Eocene foraminifera, and key palaeoenvironmental  
 1729 indicators, observed in outcrop samples. (a–e) Large, flat, rotaline foraminifera  
 1730 indicative of water depths between 20m and 50m from the Faumai Limestone. (f)  
 1731 Globular planktonic foraminifera indicative of water depths between 50m and 100m,  
 1732 Imskin limestone. (g–h) Deep-water facies containing carinate planktonic  
 1733 foraminifera indicative of water depths in excess of 100m, Imskin Limestone. Key -  
 1734 *Alveolina* spp. (A), *Asterocyclina* spp. (As), *Alveolina subpyrenaica* (A.s), *Alveolina*  
 1735 *moussoulensis* (A.m), *Discocyclina ranikotensis* (D.r), *Alveolina globosa* (A.g),  
 1736 *Planostegina* spp. (O), *Daviesina* spp. (D), *Nummulites* spp. (N), *Acarinina* spp. (Ac),  
 1737 *Globigerinatheka* spp. (Gt), *Morozovella* spp. (Mz).

1738

1739 Figure 12. Age-diagnostic Middle – Late Eocene foraminifera, and key  
 1740 palaeoenvironmental indicators, observed in outcrop samples. (a–b) Shallow water  
 1741 facies from the Faumai Limestone. (c–d) Shallow water facies observed in limestone  
 1742 lenses of the Auwewa Formation from Supiori. (e–f) Globular planktonic foraminifera  
 1743 indicative of water depths between 50m and 100m, Imskin Limestone. (h) Deep-  
 1744 water facies containing carinate planktonic foraminifera indicative of water depths  
 1745 greater than 100m, Imskin Limestone. Key – *Nummulites gizehensis* (N.g),  
 1746 *Pellatispira* spp. (Pt), *Acarinina* spp. (Ac), *Globigerinatheka* spp. (Gt), *Acarinina*  
 1747 *pentacamerata* (A.pe), *Acarinina bullbrookii* (A.b), *Subbotina* spp. (Sb), *Acarinina*  
 1748 *primitiva* (A.pr), *Daviesina* spp. (D), *Morozovella* spp. (Mz).

1749

1750 Figure 13. Palaeogeographic reconstructions of western New Guinea, showing the  
 1751 paleogeographic evolution in the (a) Oligo-Miocene; (b) Early Miocene; (c) Middle  
 1752 Miocene; and (d) Late Miocene. These maps are based on the synthesis of  
 1753 biostratigraphic data and interpreted paleodepositional environments from public  
 1754 domain well data, biostratigraphic reports, regional geology, sedimentological  
 1755 interpretations and new outcrop data. The number of data points used for each map  
 1756 are indicated in each time slice (e.g. n = 'x') and are shown as white dots. These  
 1757 data provide readers with some indication of our level of certainty for each  
 1758 reconstructions/region.

1759

1760 Figure 14. Age-diagnostic Early Miocene foraminifera, and key palaeoenvironmental  
 1761 indicators, observed in outcrop samples. (a–d) Shallow water, reefal, grainstones of  
 1762 the Maruni Limestone. (e) Shallow water packstone of the Kais Limestone. (f) Large,  
 1763 flat, roatalines indicate water depths between 20m and 50m in the Maruni Limestone.  
 1764 Key – *Lepidocyclina* (N.) *sumatrensis* (L.s), *Lepidocyclina* (N.) *brouweri* (L.b),  
 1765 *Planorbulinella larvata* (P.l), *Spiroclypeus tidoenganensis* (S.t), *Eulepidina* spp. (Eu),  
 1766 *Miogypsina* spp. (Mg), *Amphistegina* spp. (Am), *Heterostegina* spp. (Hs).

1767

1768 Figure 15. Age-diagnostic Middle Miocene foraminifera, and key  
 1769 palaeoenvironmental indicators, observed in outcrop samples. (a) Large, flat,  
 1770 roatalines indicating water depths between 20m and 50m from the Maruni Limestone.  
 1771 (b) Shallow water wackestone containing taxa indicative of water depths no greater  
 1772 than 20m. (c–d) Globular planktonic foraminifera indicating water depths between  
 1773 50m and 100m from near the top of the Maruni Limestone. Key – *Katacycloclypeus*



1774 *annulatus* (K.a), *Borelis melo* (B.m), *Globigerinoides quadrilobatus* (G.g), *Orbulina*  
 1775 *universa* (O.u).

1776

1777 Figure 16. Palaeogeographic reconstructions of western New Guinea, showing the  
 1778 paleogeographic evolution in the (a) Early Pliocene; (b) Late Pliocene, and (c)  
 1779 Pleistocene. These maps are based on the synthesis of biostratigraphic data and  
 1780 interpreted paleodepositional environments from public domain well data,  
 1781 biostratigraphic reports, regional geology, sedimentological interpretations and new  
 1782 outcrop data. The number of data points used for each map are indicated in each  
 1783 time slice (e.g. n = 'x') and are shown as white dots. These data provide readers with  
 1784 some indication of our level of certainty for each reconstructions/region.

1785

1786 Figure 17. Relative sea-level curve for western New Guinea based on average  
 1787 bathymetry calculated from reinterpreted well data compared to global sea-level  
 1788 curves of Haq and Al-Qahtani (2005), Müller et al. (2008), Snedden and Liu (2010)  
 1789 and Miller et al. (2011). Two main transgressive-regressive cycles are interpreted  
 1790 with peak relative sea-level occurring during the Late Cretaceous and Late Miocene.  
 1791 Error bars = standard error of the mean. The regional relative sea-level curve can  
 1792 also be viewed alongside the paleogeographic maps in an animation in Supp. Data  
 1793 2.

1794

1795 Figure 18. Maps showing where sections of the stratigraphic record have been  
 1796 removed at particular time slices. This includes during the: (a) Early Pliocene; (b)  
 1797 Oligo-Miocene; (c) Early–Mid Jurassic; (d) Triassic; (e) Late Permian, and (f)  
 1798 Devonian–Carboniferous.

## Highlights

- New analyses of outcrop samples and review of biostratigraphic data from public domain exploration wells across western New Guinea.
- Palaeogeographic reconstructions of western New Guinea from the Carboniferous to present day
- Regional sea-level curve for western New Guinea based on environmental and bathymetric preferences of organisms
- Two major transgressive-regressive cycles in regional relative sea-level identified, with the highest sea levels recorded during the Late Cretaceous and Late Miocene.